Optical Concepts, Inc.

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High Speed Intercomputer Optoelectronic Interconnect Modules and Data Links for Military and Commercial Applications

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The application of vertical cavity surface emitting laser (VCSEL) technology to optical communications has been the most important new development in recent times. The VCSEL offers major advantages in low-cost, low power, high-speed, high-reliability for optical communication applications. Because the VCSEL has a highly collimated emission pattern improving fiber coupling efficiency and simplifying alignment, this new device family overcomes the limitations of conventional edge emitting lasers. This objective of the program has been to develop, VCSEL array transmitters and optical receivers to be used in data links for military and commercial applications. The results obtained in this program demonstrates that serial-parallel arrays have the capability to transmit 10 Gbit/sec data rates in a quad array of VCSEL transmitters coupled by fiber to P-I-N optical receivers, with each of the four fiber optic links transmitting at 2.5 Gbit/sec, for distances up to 2 km.

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1.0 INTRODUCTION / SUMMARY

1.1 Purpose

OCI maintains a highly competitive posture in the optoelectronic market area and is introducing several new products for the communications, computing and electronics industries. The key new products are centered around an established capability in a new type of semiconductor lasers known as Vertical Cavity Surface Emitting Lasers (VCSELs). A scanning electron micrograph of a VCSEL is shown in Figure 3.1. These lasers can be manufactured and tested in monolithic form, and do not require cleaving as do conventional edge emitting semiconductor lasers. Arrays of these lasers which occur almost naturally in monolithic formats, can be used for parallel data communication links in which byte wide data is transmitted in parallel, to achieve greater than an order of magnitude increase in transmission bandwidth over conventional time division multiplexed single channel systems. The company is developing lasers for short haul applications at 780, 850 and 980 nm as well as long haul lasers operating at 1310 and 1550 nm.

The purpose of this Phase I SBIR program is to fabricate prototype High Speed Interconnect Modules and to makes measurements on these modules to demonstrate the applicability of these modules for High Speed Optoelectronic Interconnects for military and commercial use. Several vertical cavity surface emitting laser(VCSEL) transmitters were fabricated and measured using high speed optical receivers to complete a data link for transmission and bit error rate(BER) measurements. The results of the work is reported herein, showing the excellent optical performance of the high speed optical interconnect modules proposed.

Applications for these modules are many. The short haul applications include computer interconnects, free space interconnects, and fiber optic data links in parallel, serial and serial/parallel combinations. The long haul (1310/1550 nm) applications include fiber to the home, cable television signal distribution, intra continental distributed computing and replacement of the more expensive edge-emitting DFB lasers now in use in many long haul markets, particularly telecommunications. The company also has sponsored research for red, green, blue and UV VCSELs for many new applications including laser printing, high density storage, high definition displays and medical applications.

OCI has completed development of 980 nm VCSEL arrays which have modulation bandwidths >9 GHz, and have been digitally tested at 2.5 Gbps with a BER less than 10^{-11}. These 980 nm VCSEL arrays, which are suitable at distances up to 2 km using multimode fibers, are presently being prototyped and packaged for sampling to potential customers. Digital Equipment Corporation (DEC), Xerox, Tacan, Digital Switch Corporation, AMP, Inc., MOLEX Corp., GORE, ABB HAFO, Ericcson, and Microelectronics and Computer Technology Corporation (MCC) have already requested samples. Apple Computer, IBM, Intel, and many others have also expressed interest in evaluating prototypes of transmitter and receiver arrays. Even though the short haul 980 nm market will be very strong, its potential is dwarfed by that for the long haul 1310 and 1550 nm markets, which make use of a huge base of installed single mode fibers that comprise the existing telecommunication/data communication distribution network. VCSELs for

these wavelengths have proved much more difficult to design and fabricate with room temperature operating performance and efficiency. Epitaxial mirror structures at these wavelengths have lower refractive index differentials and greater optical losses resulting in much poorer vertical cavity laser performance. However, OCI, has recently applied for patents on a new long wavelength design, which promises to increase the output powers and efficiencies of the 1310 and 1550 nm VCSELs by more than an order of magnitude. Single mode powers greater than 3 mW at room temperature are predicted, thus opening up the vast Telecommunications market to low cost VCSEL arrays.

2.0 BACKGROUND JUSTIFICATION FOR OPTOELECTRONIC LINK MODULES

2.1 VCSELs for Optical Data Links

A key factor in the growth of the photonics/optoelectronic industry has been the semiconductor laser. By economic impact alone this class of lasers has become more important than any other type of laser, mainly due to the key role they play in two areas: fiber optic/laser based data communication/networking in computers and laser based long haul fiber optic telecommunications. This, however, is just the beginning of a whole new area in which the very nature and technology for electronics, computing and communications will radically change. While the lasers are produced with the cost advantages of wafer level processing, it is the packaging cost of the lasers which has dominated the final device cost and limited their penetration into the interconnection market. The high packaging cost of these conventional "edge emitting" lasers is related to their geometry. The beam is emitted from the edge of the chip, resulting in a highly diverging, elliptical beam which requires the wafer to be cleaved into bars to form the laser facets. Handling and testing the bars and coupling the light into a fiber results in high packaging costs. In addition, the long cavity length (300 μm) of edge emitting lasers (required to achieve sufficient gain for lasing), makes the lasers susceptible to mode hopping. Since the cavity is ~300 times the wavelength, a slight change in electric field and/or temperature changes the index of refraction sufficiently to cause the cavity to shift to another wavelength which then becomes the new lasing wavelength. To overcome this problem, holographic gratings are etched and then regrown into the laser structure. These expensive holographic gratings force the cavity to lase at the wavelength defined by the grating, thus overcoming the mode hopping problem. The result is a more stable laser at a much higher cost.

The high cost of a packaged, fiber coupled edge emitting laser makes it the critical component to be minimized in a cost sensitive interconnect application. Thus, optical interconnects are made using multiplexed, serialized data streams. This limits the aggregate data rate of the link to speeds practical for electronic ICs, on the order of 600 Mbit/second for silicon based ICs to 3 Gigabit/second for GaAs based ICs. The high performance and low cost of modern microprocessors is driving the development of multiprocessor / multi-tasked work station clusters which provide vast processing power at relatively low costs. A 64 channel electrical bus at 100 MHZ requires an aggregate data rate in excess of 10 Gigabit/second, and these data rates are growing daily. If multiple optical sources could be used, the electronic data rates would be kept within the range of conventional electronics so that the growing demand for high bandwidth, low cost interconnects could be met. Over the past several years our staff has been intimately involved in the development of a new class of semiconductor laser which meets these needs. Appendix A gives a more in depth background on VCSELs and their applications. How these programs and products fit with our overall market strategy and business planning are described in the following pages.

2.2 R & D STRATEGY

Optical Concepts' research strategy is to build upon demonstrated leadership in 980 nm wavelength VCSEL performance to develop VCSELs at other wavelengths and the products that benefit from their unique qualities. More than simply benefiting from our knowledge of the design and development cycle of the 980 nm laser, 1300 nm, 1550 nm and 450 nm VCSELs are under development which use the 980 nm laser as the active engine. Integrated cavities are then used to convert the wavelength either by optical pumping or frequency doubling processes. The advantages of this strategy are twofold. First, the company research maintains focus on the performance of the 980 nm laser, supporting their development and transfer to manufacturing. Second, progress made in the manufacturing activities will directly benefit the research device performance, reducing the technological risks.

As the markets saturate in 980 nm VCSELs for optical interconnects, 980 nm fiber amplifier pumping, etc., the alternate wavelength lasers will provide access to additional markets while directly building on the manufacturing, packaging and reliability improvements of the more mature vertical cavity laser technology. In addition, the company is leveraging its ability to produce vertical cavity lasers to develop optimized transmitter and receiver modules including the detectors and application specific integrated circuits (ASICs).

While drawing staff with experience in the leading research centers, Optical Concepts small business classification allows us to take advantage of government sponsored Small Business Innovative Research (SBIR) and other programs which support the development of "dual use" technologies. Improved optical data link products are valuable in both government and commercial computing and communication markets, making them ideal dual use technologies. The company works closely with the Optoelectronic Research Center at UC Santa Barbara and the Sandia National Laboratories, which conduct a broad scale state-of-the-art research effort in this field. The company has funded research programs with both of these institutions, and is also working with larger companies such as Xerox and Honeywell to participate in larger funded research programs. The acceptance of Optical Concepts by these larger established corporations speaks well for the caliber of our staff and capability.

Consistent with minimizing the financial impact of research on the manufacturing operation, Optical Concepts targets specific research areas in which programs directly augment the development necessary for new products with both government and commercial market potential so that government funding is available. Optical Concepts is already under contract to the government in many important areas:

1. 850 and 980 nm VCSEL Arrays for Parallel Optical Data Links for Computing.

2. Multiple Wavelength 1550 nm VCSEL Arrays for Continental Distributed Computing Applications (National Information Infrastructure/NII.)

3. Blue-UV VCSELs for very high density optical read-write data storage.

4. Red VCSELs (675 nm) for laser printers and other applications.

The patent process is in various stages for first three areas, allowing us to maintain a proprietary position in the coming years.

2.3 Optical Interconnect Systems Research

The most near term product where the vertical cavity lasers have a clear competitive advantage is in short haul optical interconnects. The personnel at Optical Concepts have demonstrated capability and experience in the design, development and fabrication of fiber optic communication systems. This capability covers all areas from initial system concepts to key device and integrated circuit design, device and system fabrication, characterization and test. Our personnel have developed and demonstrated the optoelectronic integrated (OEIC) receivers and laser drivers with data rates in excess of 2.5 GBPS. They have also developed the highest performance 16 X 16 optical fiber crossbar systems (OFCS) to date (500 MBPS) under a DARPA/NOSC program. This demonstrated capability and experience provide a solid basis for proceeding with more advanced optical interconnect components and systems.

More recently, IC designers have been increasing the capability of personal computers so that PCS now have essentially the capability typical of Sun (Sun Microsystems) Workstations, with further increases in capability on the near horizon. Intel has introduced commercial microprocessors with 64 bit architectures and 200 MHz clock rates, and higher speed versions are in development. To keep pace with these developments, computer designers must develop high speed-parallel data path interconnects and LANs. A new packet-switched network is also being introduced for the workstation and PC market known as the Scalable Coherent Interface (SCI), which has already become an IEEE Standard. This packet-switched network also has multi-gigabit capability, which must rely on low cost parallel optical data links using VCSEL arrays coupled through fiber optic ribbon cables.

As our manufacturing capabilities grow, it is our intent to become involved with the standards committees and enter into joint development programs with the various computer manufactures in order to become a "designed in" supplier of the physical layer components of these emerging high bandwidth data links.

2.4 Additional Research Areas

The company is also actively pursuing development of:

1. VCSEL Frequency Doubled arrays for Photoluminescent Phosphor Color Displays

2. VCSEL arrays for medical applications such as burn and wound healing, treatment of periodontal disease and other bactericidal related pain relief.

The display programs are made possible by a proprietary invention of two of our scientists, and if successful, it opens the door to high brightness Lambertian emitting color displays operating at low voltages and high optical efficiencies. These new displays would be the first display development with the potential for high brightness, high resolution flat panel displays operating at under 10 Volts, directly addressable by conventional low voltage electronic drive circuitry.

3.0 PHASE I RESULTS

3.1 VCSEL DEVICE PERFORMANCE

The optical performance of VCSEL devices were evaluated in our OCI test facilities. Modulation bandwidth measurements were made using microwave vector network analyzer and high frequency oscilloscope measurements. Bit error rate measurements were made using a 3 Gigabit/sec Bit Error Rate Tester in conjunction with a sampling oscilloscope. The performance obtained from the VCSEL devices are summarized in the following paragraphs.

For high bandwidth performance, the VCSEL design should be optimized for high frequency performance. Figure 3.1 shows an cross-sectional view of the VCSEL design used for this program. The design, shown in Figure 3.2, uses an Intra-Cavity contacted design with current constriction to minimize cavity volume while still maintaining sufficient power for the application. In addition, the design uses a semi-insulating GaAs substrate to reduce stray capacitance and capacitive coupling to the chip substrate and associated package.

The current constriction shown in Figure 3.2 not only reduces cavity volume, which reduces drive capacitance and current requirements, but also reduces optical losses resulting in lower thresholds and improved optical conversion efficiencies. This intra-cavity contacted design results in sub-milliamp thresholds, lower voltage operation, top or bottom surface emission, and no current drive through the cavity mirrors.

Figure 3.3 shows the Light Output vs, Current characteristics for various diameter intra-cavity VCSELs. As can be seen from the figure, the 5 μm, 7 μm and 10 μm VCSELs al have lasing thresholds under 1 mA, typically ~ 600 μA. The light output vs current for all three diameters is virtually identical up to output powers up to 1 mW, at which point the power becomes a function of the effective diameter which is set by the current constriction and the etch-post diameter of the device. Since the majority of both short haul and long haul applications require on 1 mW of power into the fiber, these smaller diameter devices are all adequate for data link application. In long haul applications, where single mode operation is a definite requirement, the 5 μm and 7 μm devices will operate single mode. The 5 μm VCSEL is small enough that other lateral modes cannot be sustained. In 7 μm devices a second lateral mode appears only at drive currents beyond 3 mA as shown in Figure 3.4. Figure 3.4 also shows measurements on Wall-Plug efficiencies which range from 7 to 13 %. The important point is that both the 5 μm and the 7 μm VCSELs produce single mode outputs ad moderate optical powers of 3 mW or less at high efficiencies and low drive powers and voltages. Direct or biased drive can be achieved from both GaAs at high-speeds up to 5 GHz, and silicon CMOS circuits for applications up to 300 MHZ.

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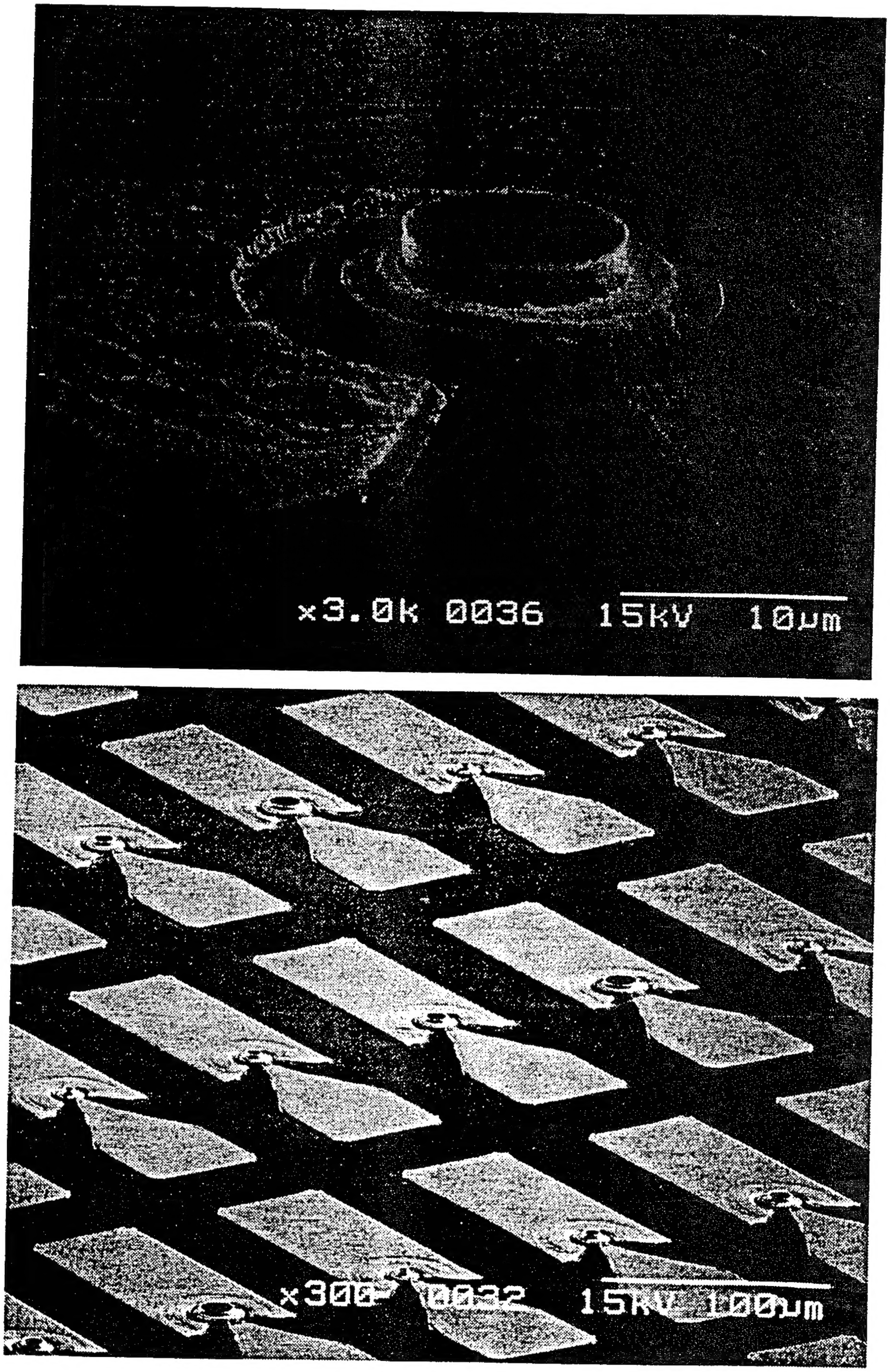
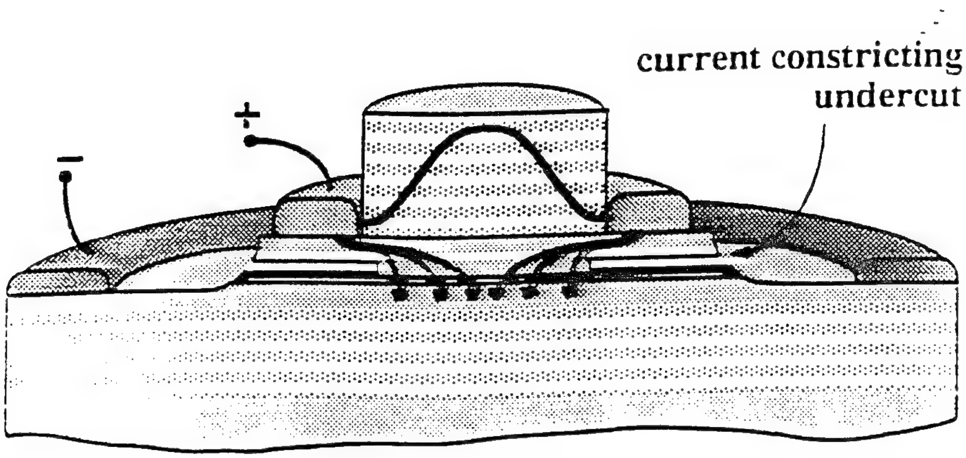


Figure 3.1

Advantages of Intra-Cavity Contacted Design

- Both contacts on the top surface
- Semi-insulating substrate
- Bottom or top surface emission
- Current bypasses mirror stacks



Resulting in ....

- High speed design
- Sub-milliamp thresholds
- Low voltage operation
- Many packaging configurations
- Current apertured designs

Figure 3.2

980 nm VCSEL

Light Output vs. Current

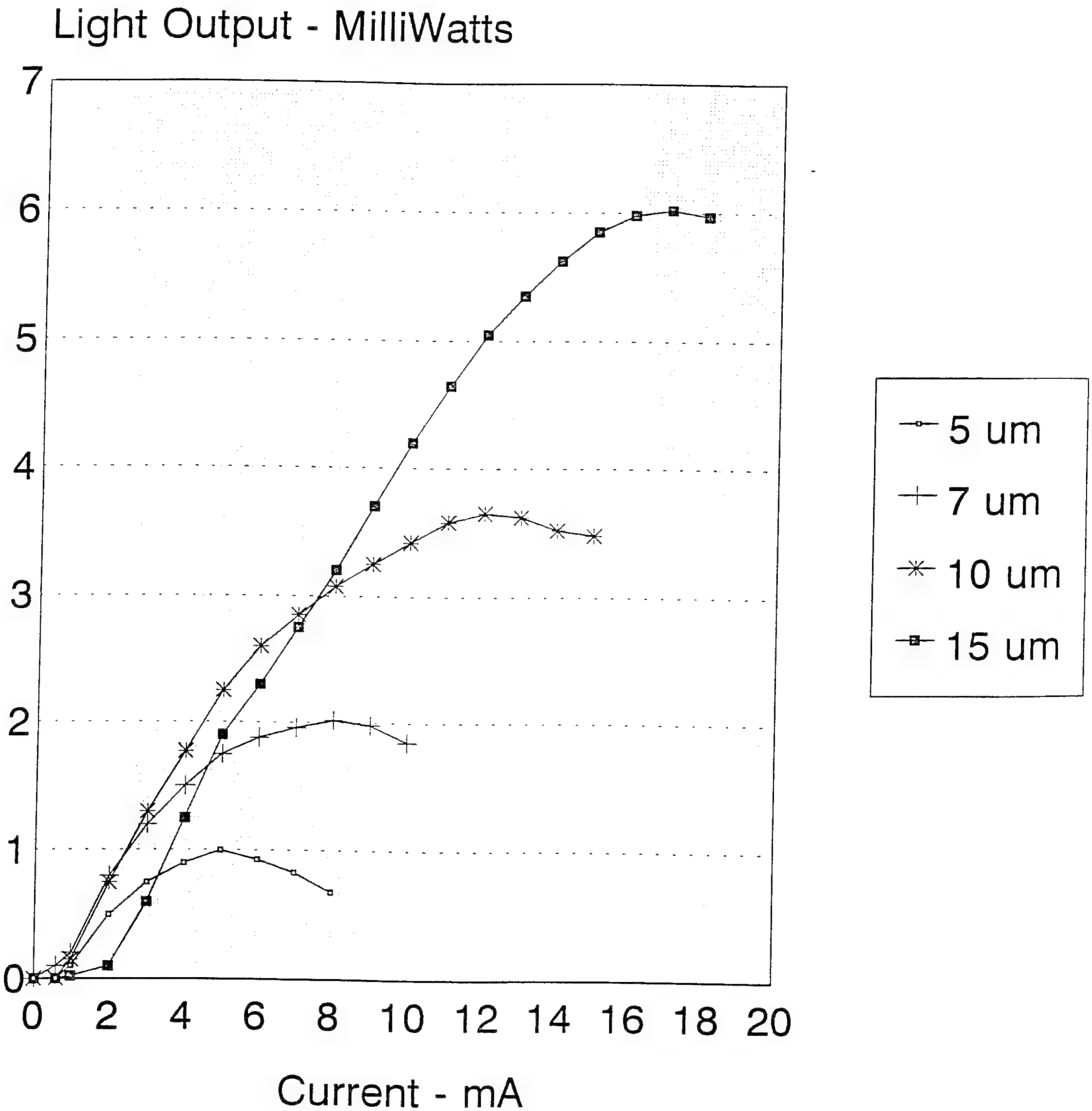
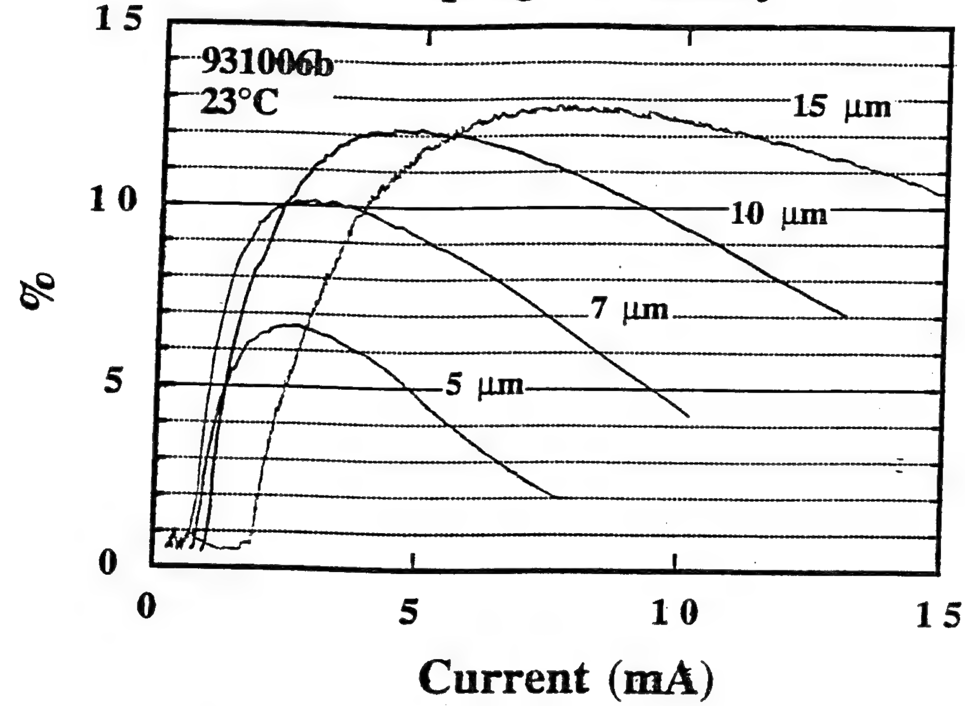


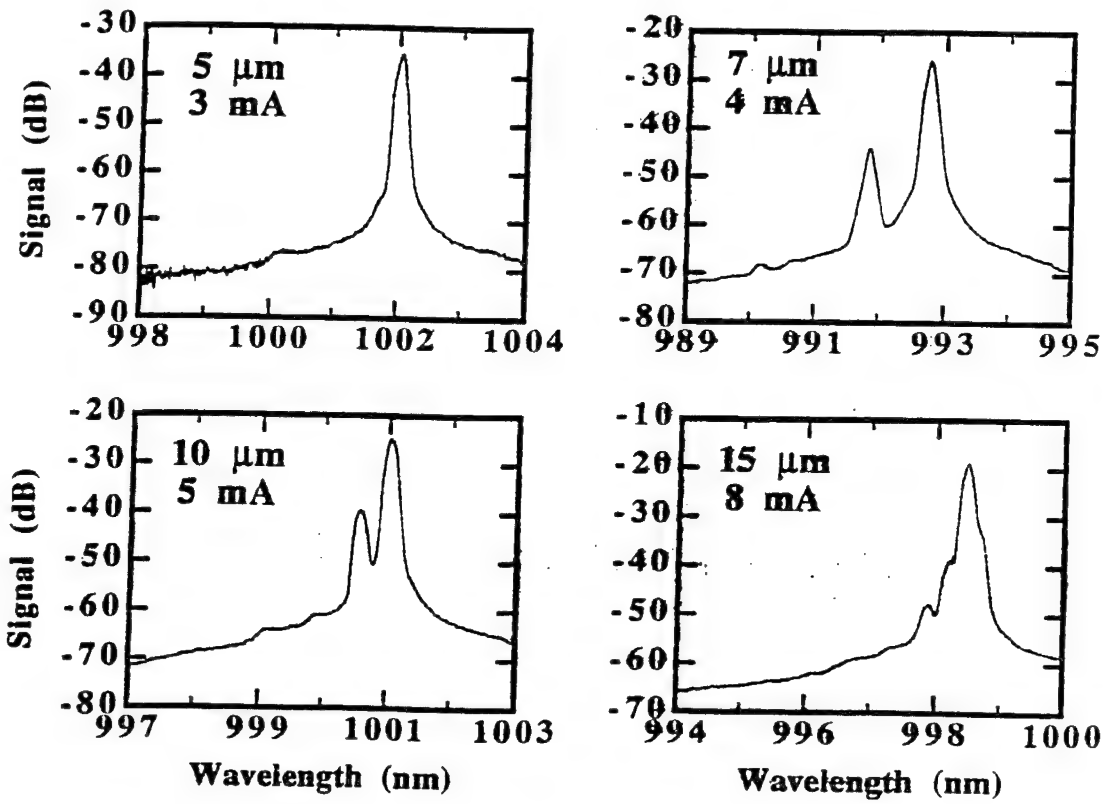
Figure 3.3

High Efficiency at Low Currents

Wallplug Efficiency



Optical Spectrum at Peak Efficiency



J. W. Scott, B. J. Thilbeaut, D. B. Young and L. A. Coldren "High Efficiency Sub-Milliamp Threshold Vertical Cavity Lasers with Intra-Cavity Contacts" *Submitted to Photonics Technology Lett. Feb 1994*

Figure 3.4

3.2 VCSEL SERIAL AND PARALLEL ARRAY LINK PERFORMANCE

To properly evaluate the VCSELs for serial and parallel link applications, a digital Bit Error Rate Test was set up in the laboratory, which allowed high speed digital testing to be done. Figure 3.5 shows the test setup, which includes high speed/microwave cascade probes for high speed laser modulation and a lensed optical pickup coupled to 30 meters of fiber cable. A 25 GHz photo diode / receiver was used to convert the optical signal from the fiber to an electronic input to the BER tester. Figure 3.6 shows the modulation bandwidth over temperature. At room temperature, the 3 dB bandwidth was measured at 9.5 GHz at only 6 mA drive current as shown in the figure. Even at 50 °C. The bandwidth was still 7 GHz. Figure 3.7 shows the eye diagram obtained at a I GHz/sec digital signal with a BER < 1x 10^{-11} using a GaAs HBT based laser driver shown in Figure 3.8. This driver array will operate at 5 GHz however, the data rate in this case was limited to the T0 18 package.

Using the high speed probe setup shown in Figure 3.5, a 4 laser array was tested, yielded the results shown in Figure 3.9. In this case, there was no package to limit the VCSEL performance and data rate were set at the standard SONET(Synchronous Optical Network) data rate of 2.488 Gbit/sec. All four devices see figure 3.9 showed no error floor, at powers above -15 dBm(~50 μW), indicating that higher data rates could be achieved with these lasers, however, the Hewlett Packard Bit Error Tester was limited to 3 Gbit/sec. The received power attenuated by the variable until errors were finally seen. At received powers above -15 dBm, no errors were detected. Data was measured or a rime period sufficient to demonstrate a 10^{-11} BER. Since no errors were detected, BERs of 10^{-15} or greater could be demonstrated with a significantly longer testing time. As the received powers were attenuated further, errors began to appear (as expected), until at - 16 dBm, the BER began to exceed 10^{-9} . For short haul data links up to two km, -5 dBm or only 300 μW of VCSEL power is needed to exceed the power necessary for error free transmission up to 2.5 Gbit/sec. At a nominal 1 mW power level adequate system margin exists for an error free system.

In single mode long haul telecommunications applications, where attenuation is much less at 1310 nm and 1550 nm, an optical power level of 1 mW into the fiber, is sufficient to have all errors attributed to chromatic dispersion rather than to signal attenuation. In other words, the chromatic dispersion causes errors before the signal attenuation in the fiber is sufficient to causes errors due to power limitations. Recently, for extreme long haul situations, the use of soliton pulse shaping has virtually eliminated the chromatic dispersion problem, allowing the use of erbium doped fiber amplifiers (EDFAs) to overcome the attenuation by optically amplifying signals allowing transmission distances > 14,000 km between transoceanic links.

OCI is pursuing these long haul applications in anther program with US army SDC. Section 4 below will discuss the requirements for data links in Phase II of this program.

Bit Error Rate Test Bed

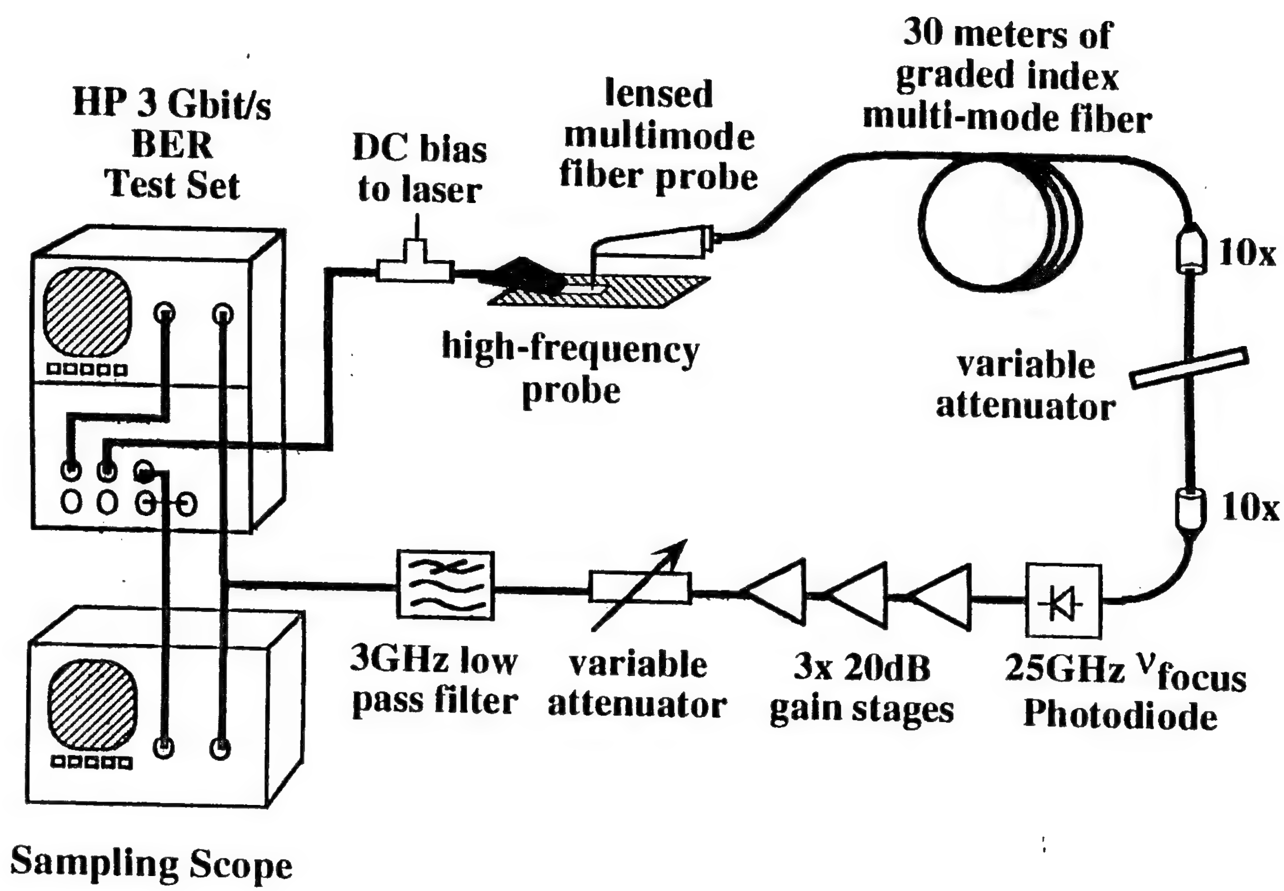
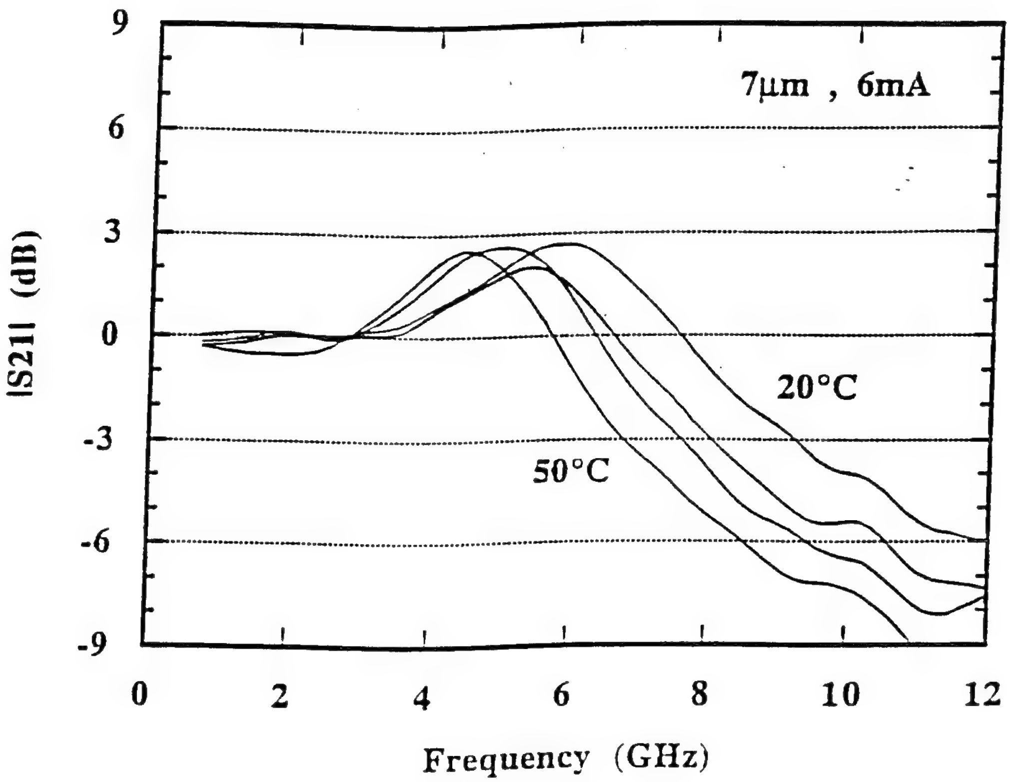
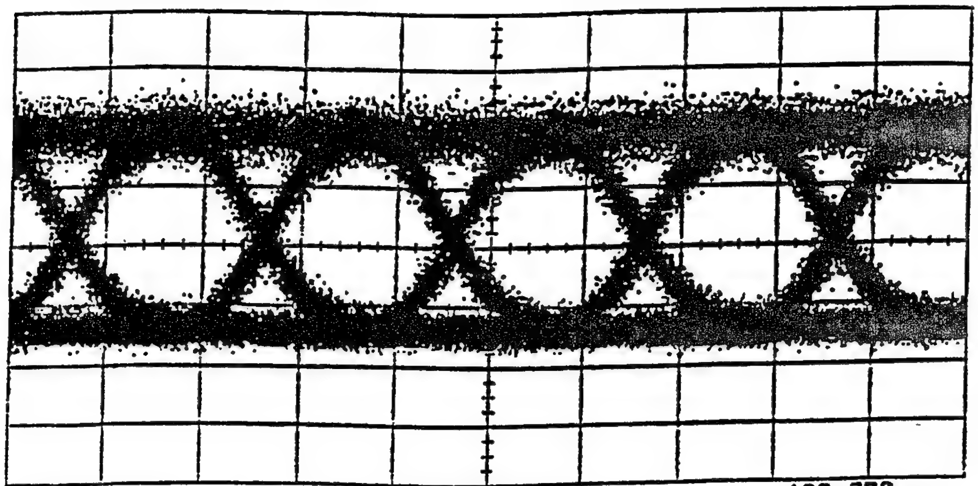


Figure 3.5



Modulation Response @ 6mA Drive Current

Figure 3.6



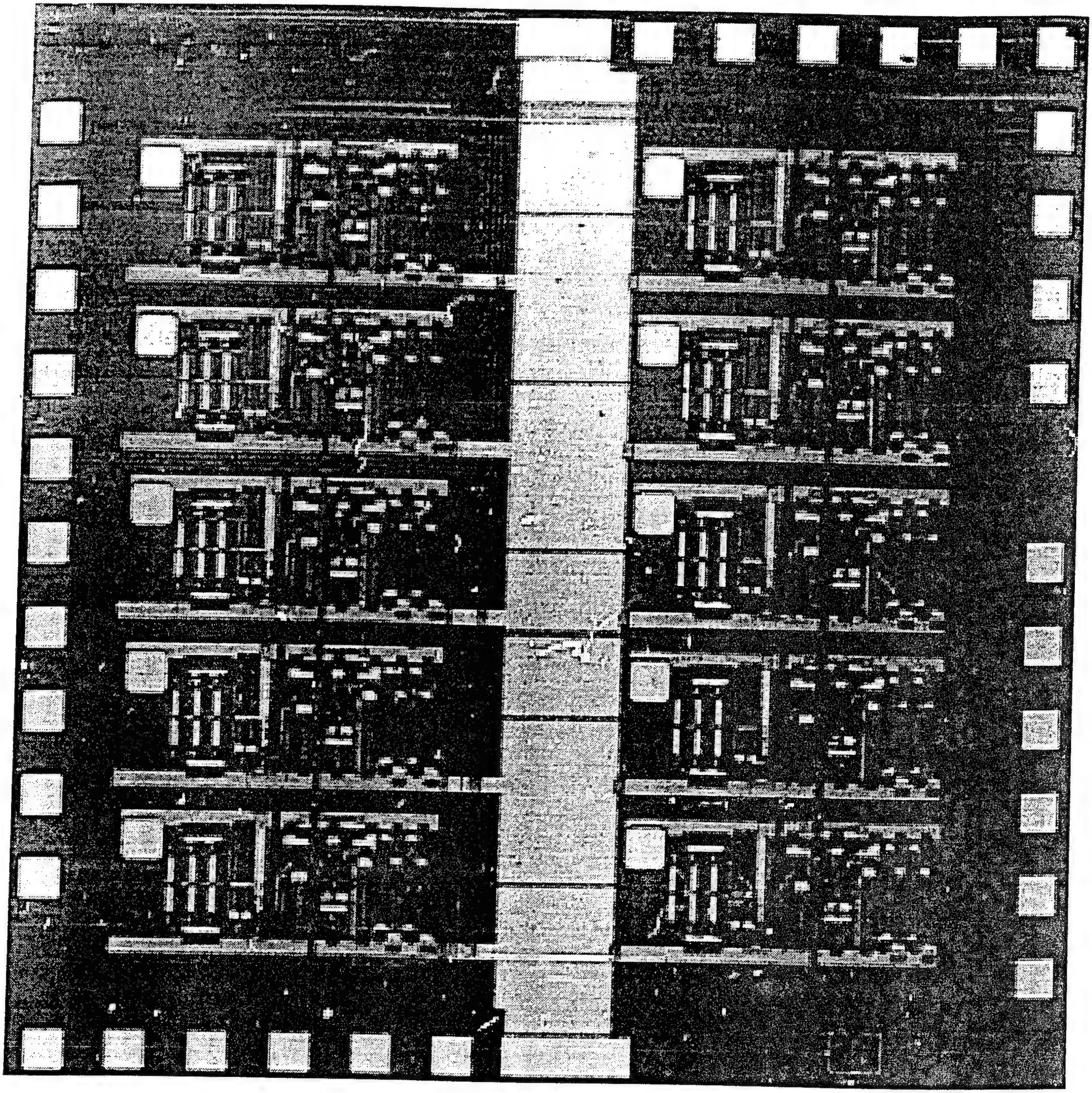
Ch. 4	=	250.0 mVoits/div	Offest	=	2.035 Voits
Timebase	=	500 ps/div	Delay	=	105.720 ns

Trigger on External at Pos. Edge at -435.0 mVoits

Idc	=	10mA
Vmc	=	1 V P-to-P
Vcc	=	6.0 V
Vrd	=	-5.1 V

Data Rate Measured at 1GB/Sec at BER = 1×10^{-11}

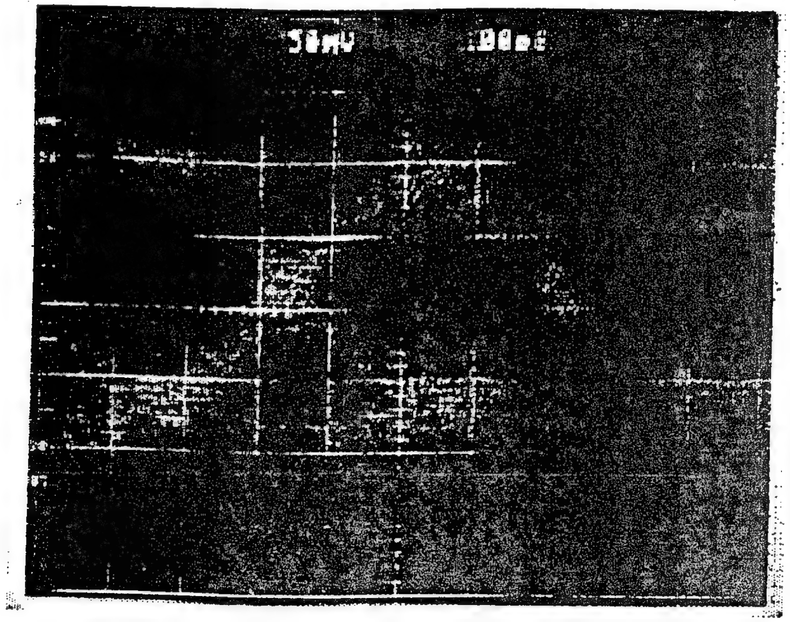
Figure 3.7



1x10 Laser Driver

Figure 3.8

High Speed Digital Data Links



eye diagram for 5 μm device, received opt. power -14 dBm

- All four device sizes showed no error floor
- Measurements made with 30 meters of multimode fiber

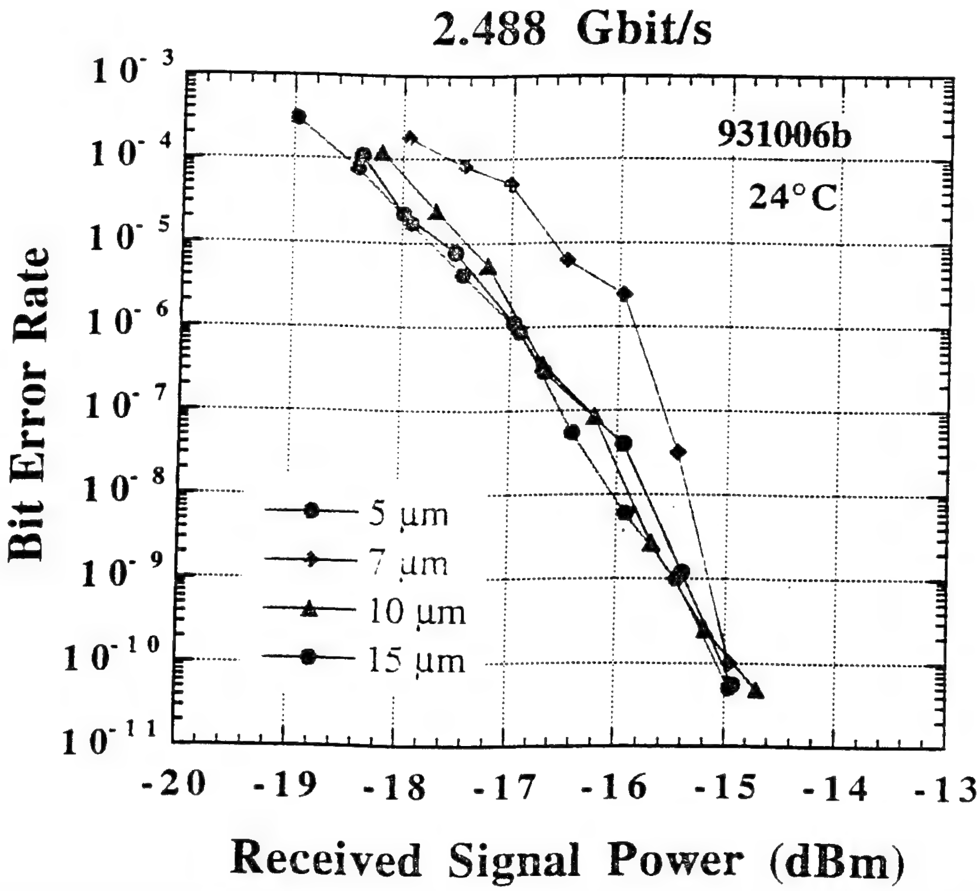


Figure 3.9

4.0 PROJECTED PHASE II DESIGN

In considering the optimum design for parallel, serial and serial-parallel combination data links, the particular application will dictate the type of link which will ultimately be applied. A key factor in any link design is the performance/cost ratio. In short distance applications of only a few meters, parallel links are preferable for wideband performance. For longer haul applications the link design will vary depending on bandwidth and distance requirements.

4.0.1 LINK SYSTEM DESIGN

Figure 4.0.1 shows the basic parallel link schematic diagram. In this case the transmitter consists of digital interface circuitry which provides digital input format for a parallel driven VCSEL array. The digital output is coupled to a laser driver array IC, of either GaAs or Silicon, depending on bandwidth requirements. The laser driver IC provides a current source drive for each VCSEL in the array. The output of the laser array is coupled to a fiber ribbon cable. The receiver inputs the signal form the fiber ribbon cable to a P-I-N detector array which can be either InGaAs or silicon depending again on bandwidth requirements and the laser wavelength of the link. In determining the overall design of the link, cost is an over-riding factor. In telecommunications applications, relatively high cost links are economically feasible since the link cost is amortized over millions of long distance calls or television transmissions. In data communications between computers and buildings, the link cost must be low enough to be practical for computer to computer and even memory to processor applications.

4.0.2 COST/PERFORMANCE TRADE-OFFS BETWEEN PARALLEL, SERIAL AND SERIAL/PARALLEL DATA LINKS

The successful application of fiber optic data links in lower cost applications other than telecommunications markets depends heavily on the ability to provide affordable system designs which, of course. Ultimately determines the type of link for each type of application. It was first thought that parallel links, which offer the advantages of simplicity of design, low latency and other advantages, may become the accepted norm for multimode links up to 2 kilometers in length. However, as the technology developed in VCSEL arrays, receiver arrays, and parallel fiber ribbon cable, a series of cost factors, not previously anticipated, began to affect the economic trade-offs between serial and parallel designs. The cost of the optoelectronic components have fallen significantly as expected with the maturing of the manufacturing process, and the encouraging data obtained in reliability testing. The speed of both silicon CMOS and GaAs based IC laser drivers, receiver amplifiers, switching, and digital interfacing circuits have all greatly improved both from a performance and cost standpoint. In fact, with the establishment of several GaAs foundries, these circuits are now cost comparable to their silicon counterparts until the volumes become quite large.

The unexpected problem in the cost of the overall parallel system approach arose from the skew problem in parallel optical fiber ribbon cables. With ribbon fiber manufactured from normal stocks of fiber, the skew/meter (~10 picoseconds/meter was far too great to used for all but very

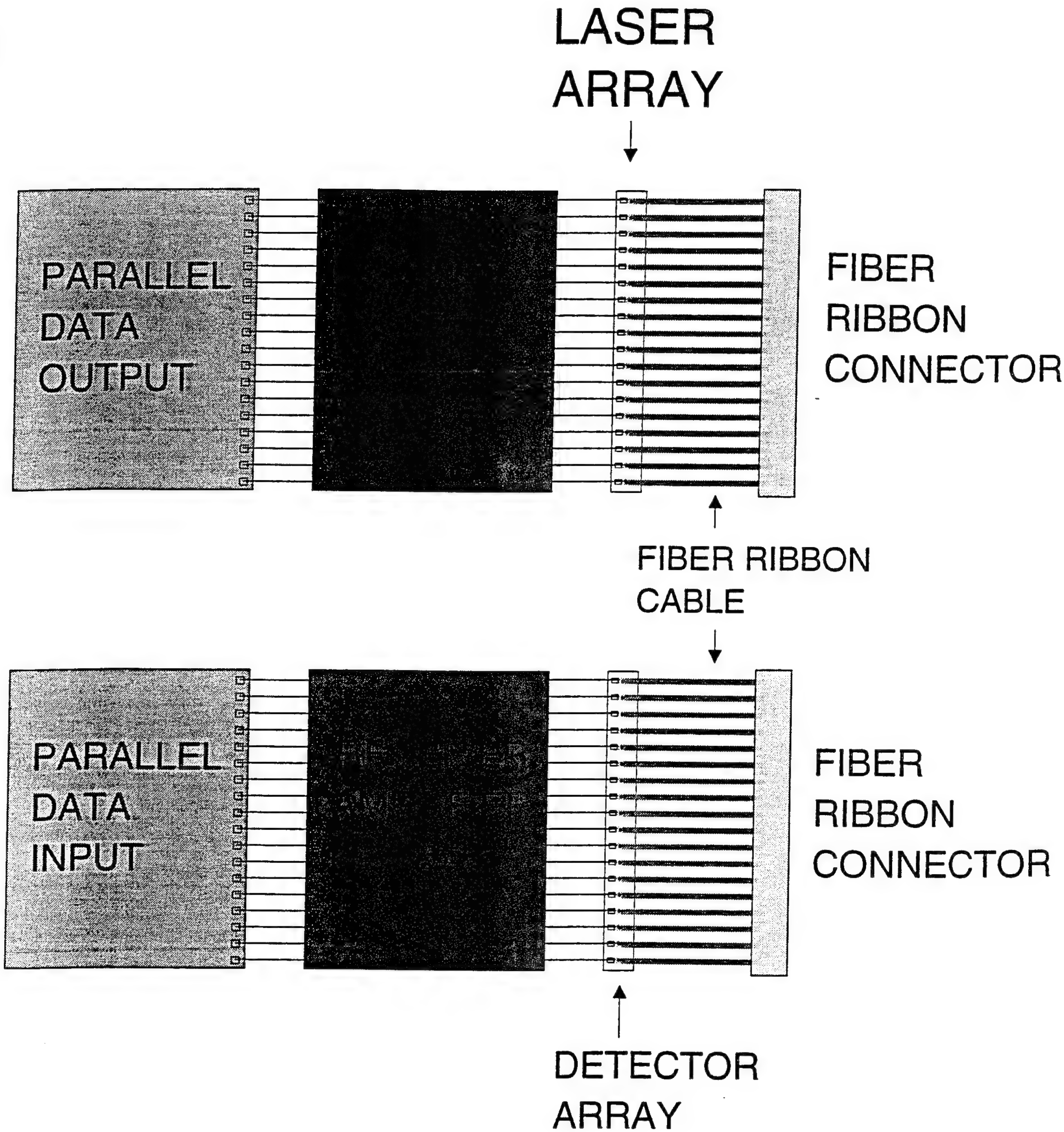
short distances of a few meters (ps/m). Fiber manufacturers were able to reduce the skew problem to ~ 1 ps/m by using fiber drawn form the same boule, however, the increase in cost for this process was significant. All fiber had to be rigorously tested for uniformity of index of refraction vs. temperature and effective skew and carefully matched before it could be used in ribbon cables.

As a result, the cost of fiber ribbon cable went up sharply to ~$7.00/m as compared to only ~$0.20/m for single mode fiber cable used by the telecommunications industry. The $0.20 cost shows what is possible with large volume manufacturing. Figure 4.0.1 shows the impact of fiber ribbon cost on link cost as a function of link distance. At small distances of a few meters the costs are comparable between a 10 GHz link 12 channel parallel link and a 4 channel serial/parallel combination using single mode fiber cables. Since each serial branch link in the serial/parallel architecture is transmitting data stream, a synchronization of parallel bits is not needed. Therefore, low cost single mode fiber can be used. To obtain the same total transmission bandwidth as a 12-up parallel system, 4 serial channels of 2.5 Gbit/sec. data are used for cost comparison. For bandwidths up to 2.5 Gbit/sec, only 1 serial channel is required. The data is multiplexed up 4X prior to transmission and demultiplexed by 1/4 to obtain the 4 channels at the receiving end. Latency is minimal when compared to the transmission time in most cases. The cost of the mux/demux circuitry in the ser/parallel approach is offset by the savings of requiring fewer laser transmitters and receivers. For all link distances over a few meters in length the Serial/Parallel single mode transmission design has a distinct cost advantage over the parallel design. Therefore, the Serial Parallel design will be the successful approach for this market. Many other manufacturers have already made similar conclusions. The designs presented in the following sections are based on the serial/parallel combination link.

4.1 VCSEL DATA LINK CIRCUIT REQUIREMENTS

4.1.1 2.5 Gigabit Optical Computer Link Circuits

The next generation microprocessors and networks will place heavy demands on both processing and communications capabilities. Typical requirements are high aggregate processing rates, multiple concurrent high data rate I/O capability and low latency. All of this will need to be achieved with low bit error rates. With microprocessors exceeding 300 MHZ and symmetric multiprocessing (SMP) designs in place, a link for much higher frequencies needs to be developed now to satisfy the needs of tomorrow's computer systems. To this end, we have designed a 2.5 Gigabit optical link using VCSEL laser, InGaAs photodetector and GaAs MESFET circuit technologies to design the lowest cost, lowest power and most efficient computer link that will provide the necessary bandwidth for tomorrow's computer needs. The components of this design can be configured for both fiber ribbon links and free space optical links which provides the flexibility necessary to better serve the application. This section will focus on the circuit design for this link which includes both receiver and transmitter module designs.



PARALLEL OPTICAL DATA LINK CARD

Figure 4.0.1

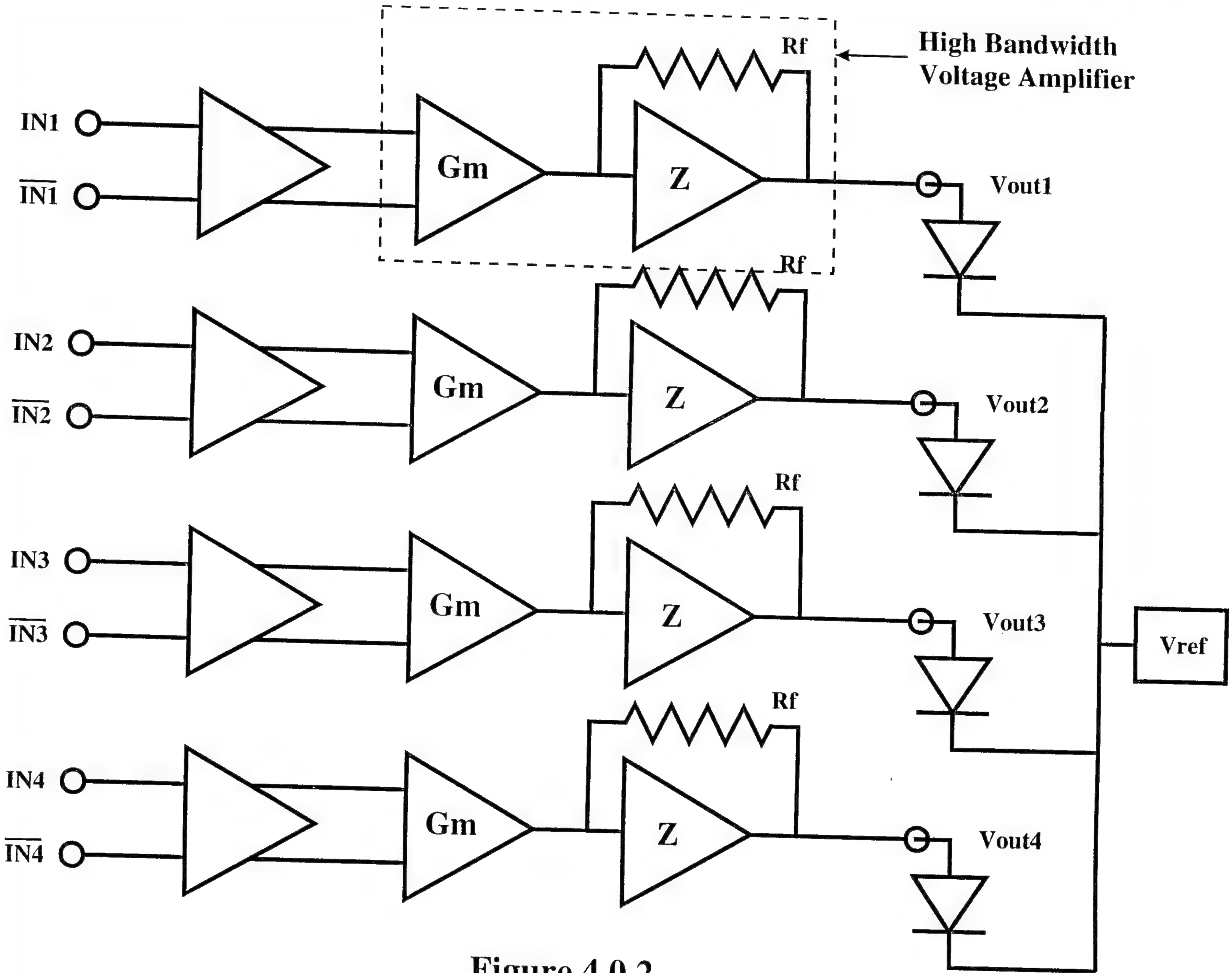

High Bandwidth
Voltage Amplifier
IN1
$\overline{IN1}$
IN2
$\overline{IN2}$
IN3
$\overline{IN3}$
IN4
$\overline{IN4}$
Gm
Z
Rf
Vout1
Vout2
Vout3
Vout4
Vref

Figure 4.0.2

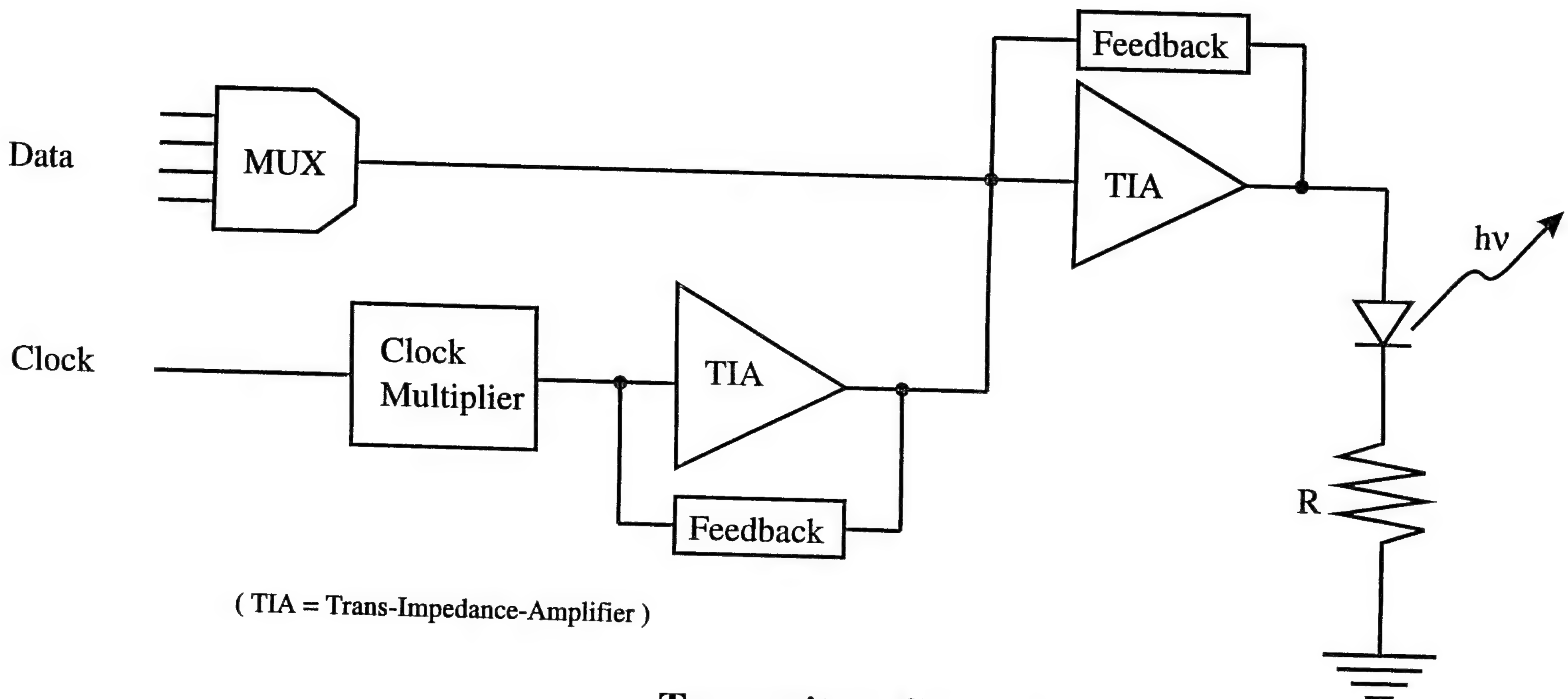
4.1.2 2.5 Gigabit Transmitter module.

Each transmitter channel consists of a 4:1 Mux with input buffering (includes ECL compatibility) and encoding, a transimpedance amplifier (TIA) and clock generator circuit (shifts the clock up to a

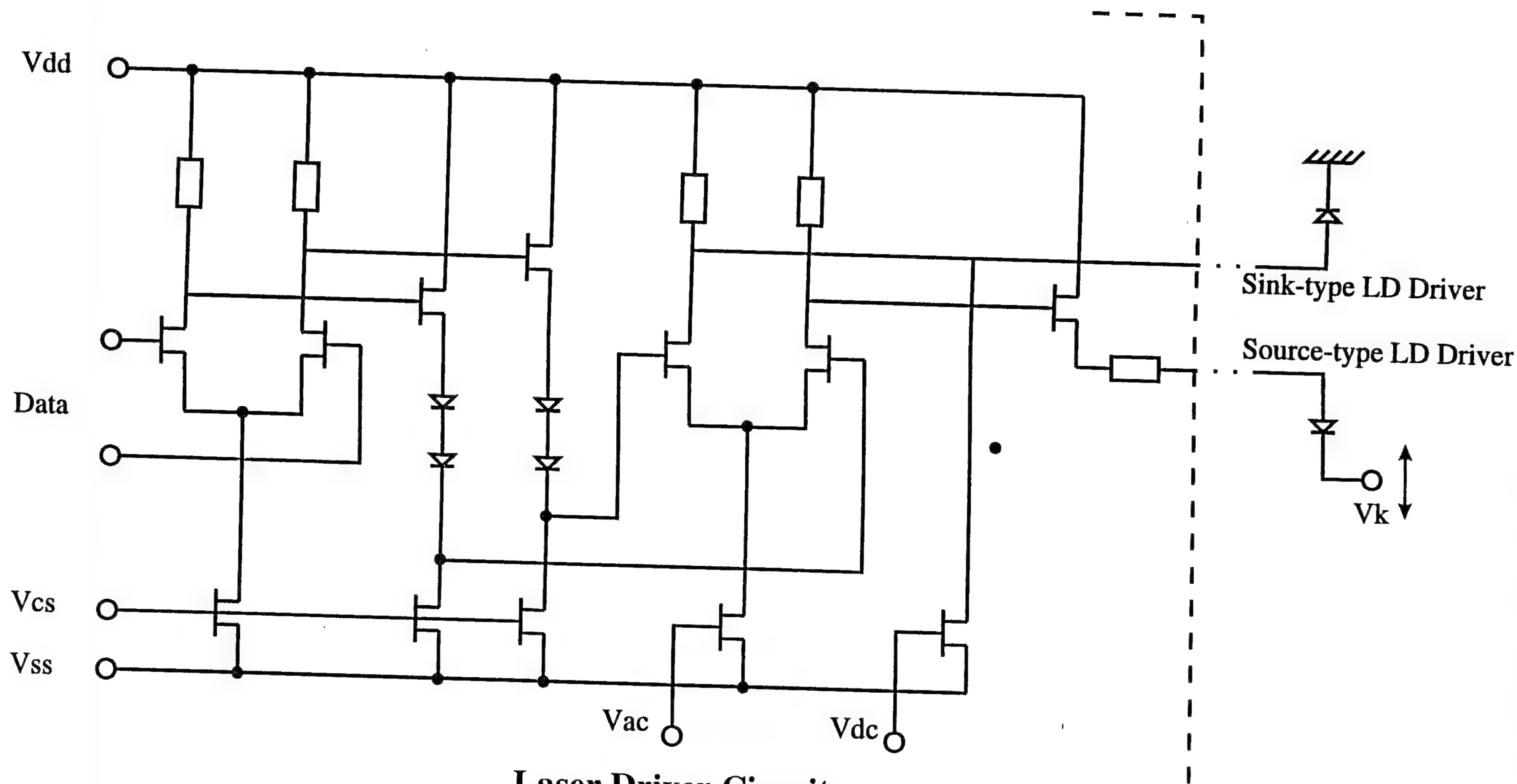
higher frequency for sinusoidal transmission) and another TIA amplifier to sinusoidally drive the VCSEL. See figure 4.1.1 for a circuit of the transmitter channel. The excessive bandwidth of the VCSEL (>8 GHZ) allows the addition of a sinusoidal clock signal to be modulated on top of the data stream which alleviates the need to have a separate line to transmit the clock. . The Preamp and Decoder circuits are shown below in Figures 4.1.1, 4.1.2 & 4.1.3. The input buffering/mux design will be borrowed from Vitesse Semiconductor and is already tested and verified. We are also currently investigating power feedback management to compensate for possible degradations in optical power output of the lifetime of the VCSEL. As yet, our VCSELs are not showing any significant lifetime degradation, but more thorough reliability testing will be the final determination of effective lifetimes. Some new studies indicate that VCSELs will have effective lifetimes > 50 years. *(Diode Lasers and Photonic Integrated Circuits, Coldren & Corzine, John Wiley & Sons, 1995)*

Each receiver channel consists of a InGaAs photodetector, a low pass filter (LPF) and clock regeneration circuit, a preamp, a postamplifier with level restoring, a buffer, a decision/decoder circuit and finally a demux with four off-chip buffer/drivers. See figure 4.2.1 for a circuit of the receiver channel. The InGaAs photodetectors are low capacitance, high speed devices which also provide the bandwidth necessary for our novel clock recovery design.

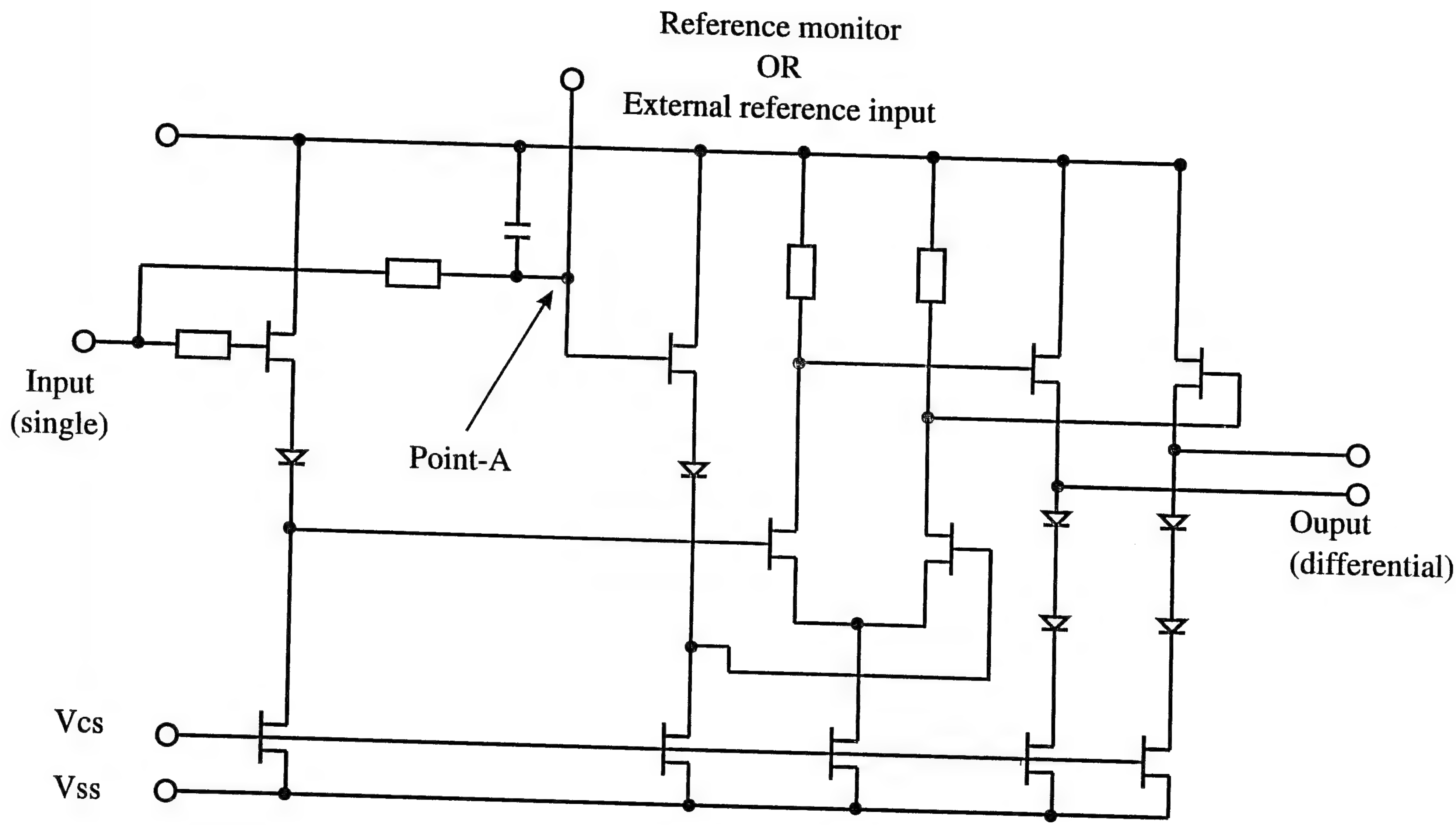
A novel clock recovery scheme (Courtesy of Dr. Richard Nottenburg of Multilink Technology Corporation) is applied to take advantage of the excessive VCSEL bandwidth which will exceed 8 GHZ. Due to the small signal high modulation bandwidth (~ 10 GHZ), the clock signal can be generated at 4X the data rate by sinusoidally modulating the VCSEL at a frequency well above the data stream. The clock signal may then be superimposed on the data stream. As shown in Figure 4.1.4. This clock signal may then be used to reconstruct the digital clock at the receiver end prior to its removal from the data stream. The low pass filter simply removes the high frequency sinusoidal clock from the data stream. The data stream is then capacitively coupled into the Preamp to eliminate DC offset problems. Following this, the preamp converts the incoming signal to voltage which is then buffered by the Postamp and Buffer to sufficiently drive the decoder. The decoder/decision circuit then decodes the signal to provide a digital data stream which is then demuxed (1:4) back down to 622 MHZ for the subsequent system. The Preamp and Decoder circuits are shown below in Figures 4.2.2 & 4.2.3. The Postamp is a limiting amplifier with an automatic gain control feedback configuration which also squares up the output waveform. The buffer provides the necessary current drive capability required by the Decoder. Finally, a demux design, from Vitesse Semiconductor, will divide down the data stream.



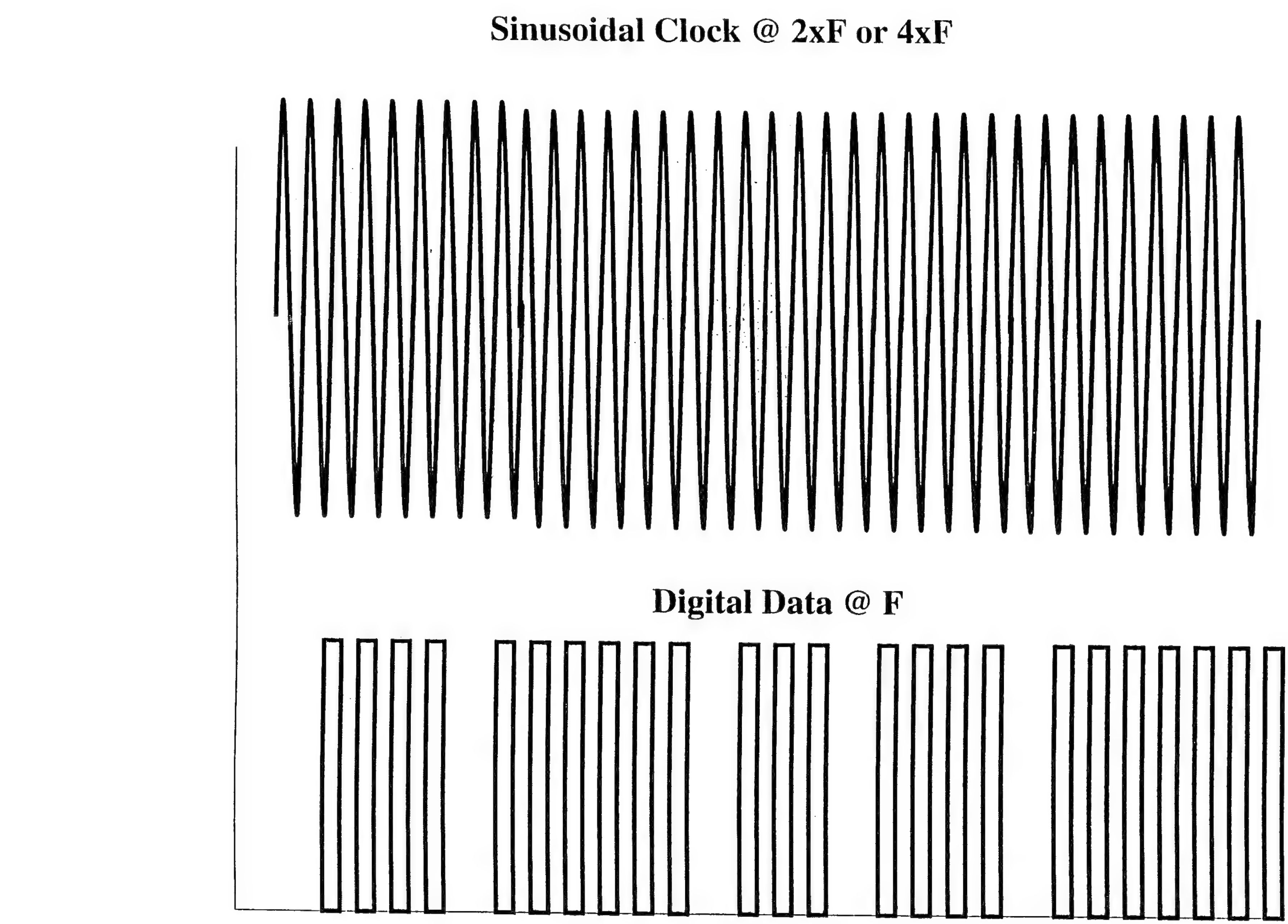
Transmitter Channel
Figure 4.1.1



Laser Driver Circuit
Figure 4.1.2

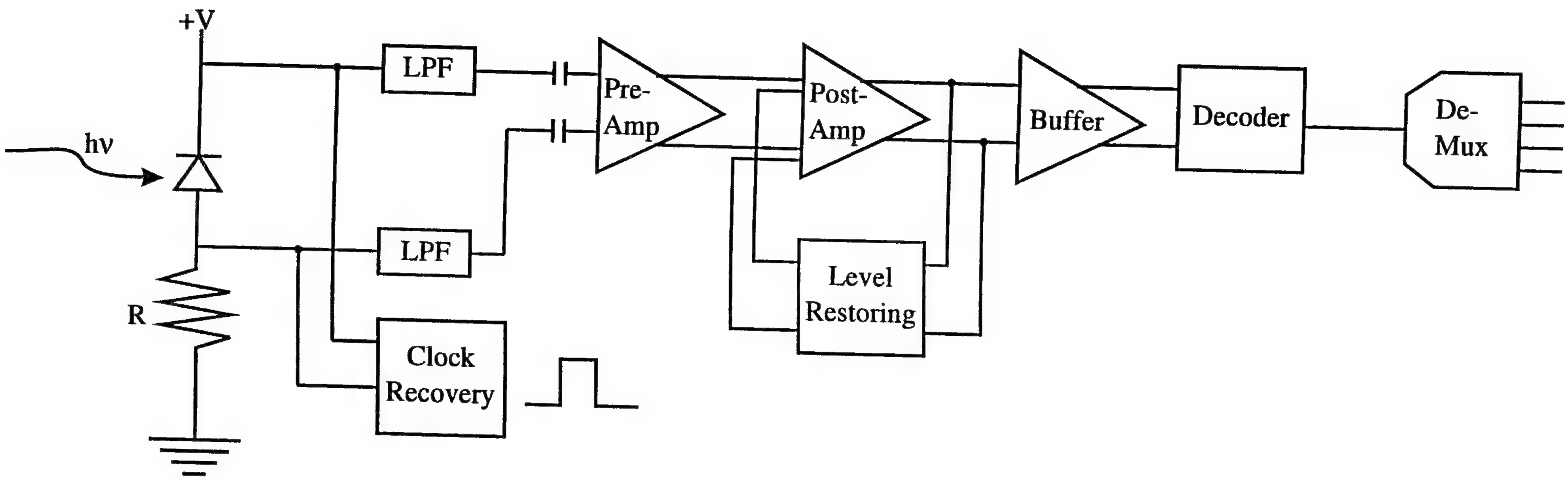


Threshold Determination Circuit
Figure 4.1.3

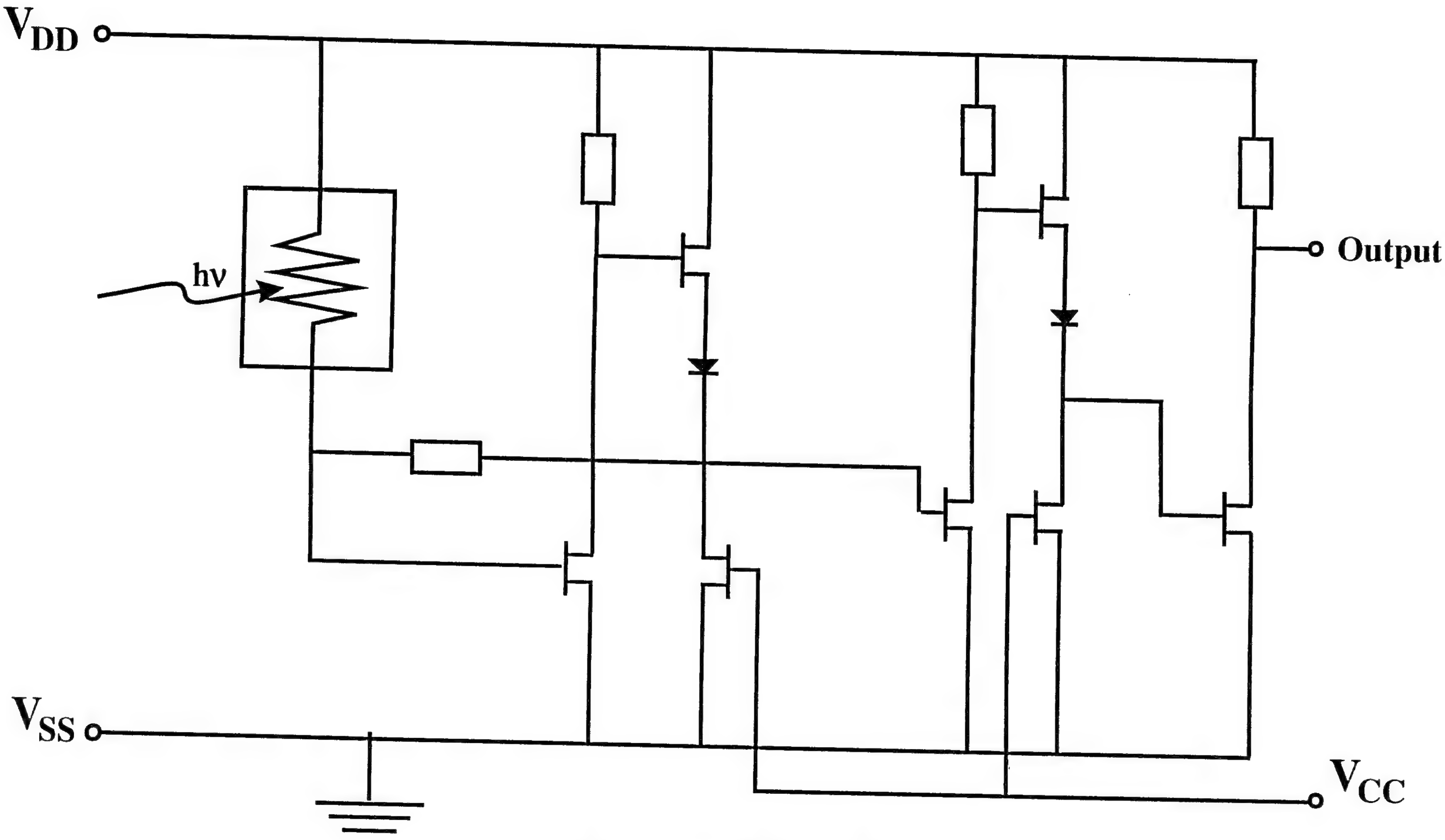


Clock & Data Recovery Using Omnipresent Sinusoidal Clock

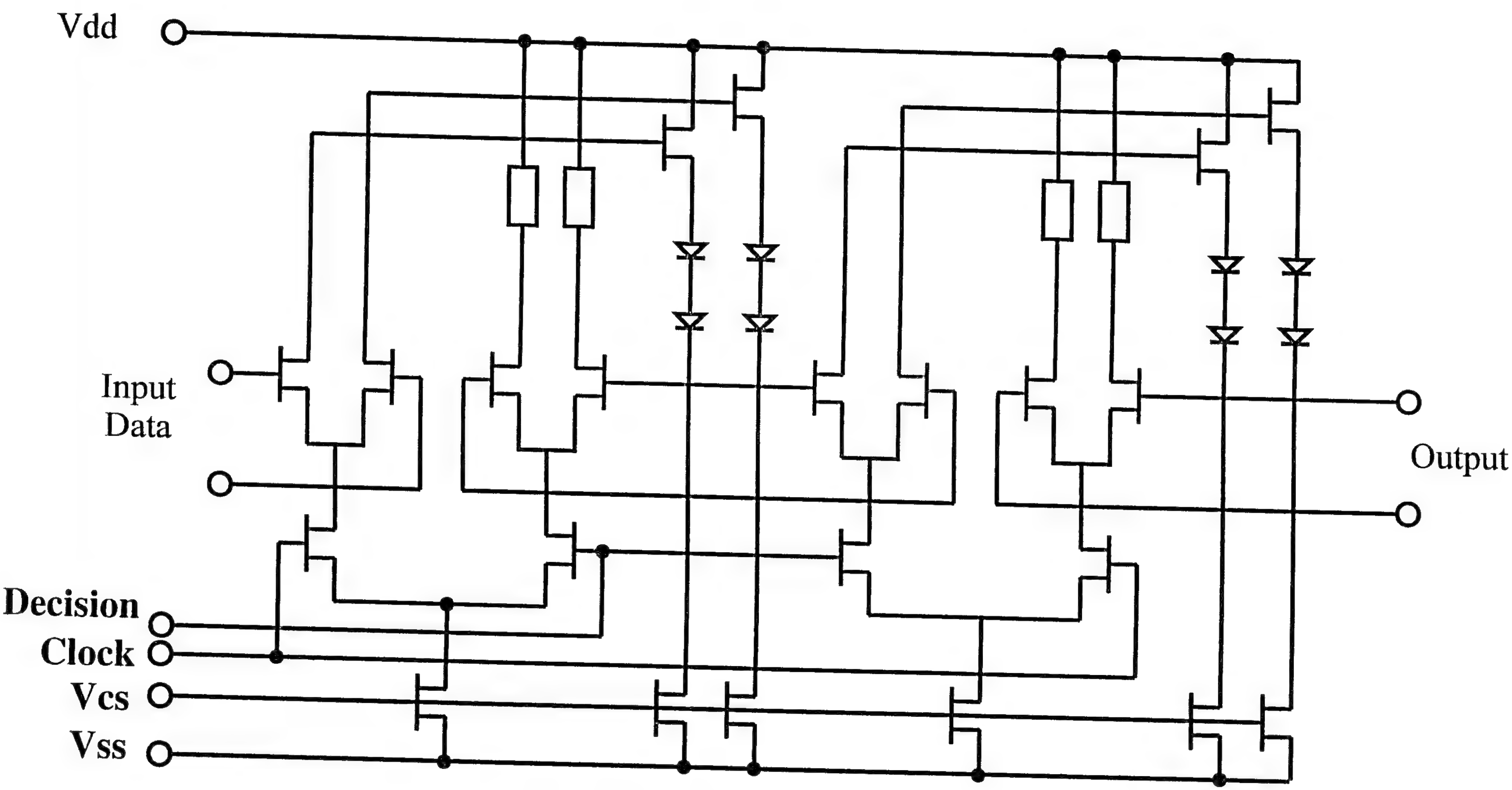
Figure 4.1.4



Receiver Channel Circuit
Figure 4.2.1



Preamplifier Circuit
Figure 4.2.2



Decoder (Decision) Circuit
Figure 4.2.3

4.3 CONCLUSION

In conclusion, we have developed a chip set for multiplexing four 622 Mbit data streams onto a 2.5 Gigabit optical link for either free space or ribbon fiber connections. These circuit building blocks can be broken out into separate ICs (integrated circuit) for a more flexible modular approach or they maybe combined for the most compact integrated solution. Although the circuitry has been designed it has not been verified nor has it been tested. In phase II of this contract we hope to simulate, layout, verify and test this chip set with VCSEL lasers and InGaAs photodetectors to provide the lowest power, most efficient and most affordable high speed link available. Such a link will surely be needed for computer systems in the very near future.

APPENDIX A

TECHNICAL BACKGROUND

FOR

VERTICAL CAVITY

SURFACE EMITTING

LASERS

VERTICAL CAVITY SURFACE EMITTING LASERS

A semiconductor laser, which has a vertical cavity and emits a circular collimated beam normal to the surface of the chip has been recently developed. This surface emitting laser, unlike previous edge emitting lasers, has a self contained high reflectivity mirror structure to form the cavity and therefore does not require cleaving, allowing arrays to be fabricated in any pattern desired. Progress in these vertical cavity lasers has been very rapid in recent years. The advantages of wafer scale probing, inherent single longitudinal mode operation and easy optical coupling make vertical cavity lasers very attractive as low cost sources for such applications as computer interconnects. The development of high reflectivity semiconductor mirrors has made these short cavity devices possible. Using modern epitaxial techniques such as molecular beam epitaxy and metal organic vapor phase epitaxy, layer thicknesses can be precisely controlled to a degree impossible to achieve by photolithography. A vertical cavity, therefore, can be controlled much more precisely than that of a horizontal cavity of a conventional in-plane semiconductor laser. Once grown, the laser's vertical cavity is complete, needing only to be etched to a small size and contacted. Thousands of lasers can be made and tested all on a single wafer.

A typical in-plane laser is about 300 μm long, or about 2000 half wavelengths of the lasing mode. The next mode will have 2001 half wavelengths in the cavity, or a 1/2000 change in frequency. The modes are thus closely spaced, and hence many are amplified by the active material. When an in-plane laser is driven at high speed, the other modes become excited, resulting in linewidth broadening and limiting the maximum data rate. To avoid this problem, process intensive gratings and regrowth are used, making high speed lasers very expensive. A vertical cavity laser, in comparison, has only ten half wavelengths in its cavity, resulting in only a single longitudinal mode that is amplified by the active material. A vertical cavity laser is inherently a single frequency laser, although some form of transverse mode control is required. Another important quality is the beam divergence. In-plane lasers require lenses and careful alignment to be efficiently coupled into optical fibers or waveguides because the light is emitted from a narrow aperture, resulting in a beam divergence of ~45°. While vertical cavity lasers are small, their aperture is large compared to the optical wavelength, and the light is emitted in a tight cone with an overall divergence angle of ~6°, making them ideal for coupling into fibers and waveguides or integration with arrays of microlenses.

Yet another important feature of vertical cavity lasers is their ability to operate over a wide temperature range with stable output power. This temperature stabilized operation is directly related to their single mode operation and the accuracy possible in the control of the cavity dimensions. In comparison, a conventional in-plane lasers output always increases with increasing temperature, requiring the inclusion of optical monitoring and feedback /or temperature control in the laser module. Vertical cavity lasers enable the development of simplified transmitter modules and control circuitry. This advantage is even more important as one considers the development of low cost multi-element transmitter modules.

Lastly, the very small volume of a vertical cavity enables the lasers to modulate at high frequencies with very low drive currents. Combined with low threshold currents, high speed

data rates can be achieved with simple on/off modulation of the lasers with currents of only a few milliamps. In a close collaboration with UC Santa Barbara, Optical Concepts has developed a class of intra-cavity contacted vertical cavity lasers which have demonstrated these characteristics. A scanning electron micrograph of one of the lasers is shown in Figure. A1. These arrays of lasers were fabricated on semi-insulating GaAs substrates to make them both high speed and practical for integration with electronics in hybrid packages.

The lasers were designed to minimize the current needed to obtain useful output power. The experimental current to light (LI) characteristics are shown in Figure. A2 and their power conversion efficiencies in Figure. A3. Of particular interest is the 7 μm diameter laser which has threshold currents below 1 milliamp and power conversion efficiency of 10% at a few milliamps. The lasers had bandwidths in excess of 8 GHz at a bias of 4 mA, making them ideal for high speed data transmission. Their bandwidth increases with input current at a rate of 5.7 GHz/mA, higher than any edge emitting laser reported to date. Using the unique characteristics of these vertical cavity laser arrays, high speed bit error rate measurements were made on-wafer using electrical and optical probes. The optical probe was a lensed multimode fiber held 50-100 μm above the surface, showing that automated testing of the lasers is indeed practical on a wafer scale.

An eye diagram at 2.488 Gigabit/second is shown in Fig. A4 for the 5 μm diameter laser at a received power of 0.04 mW. All four laser sizes operated as expected up to the maximum system data rate of 3 Gigabit/second with no bit error floor observed. To test the performance under simplified driver conditions, the 7 μm diameter lasers were modulated under identical, full on/off conditions (0-6 mA) at 1.6 Gigabit/second for stage temperatures of 20-60°C showing identical bit error rate characteristics as shown in Figure. A5. The design of these lasers has been patented by Optical Concepts along with improved designs for higher powers, better efficiency and transverse mode control. These InGaAs vertical cavity lasers, operating at wavelengths near 1 μm, are ready for transfer to commercial manufacture and form the basis of our near term product line. Leveraging off this success, our research is pursuing the extension of the vertical cavity laser into other wavelength regimes. Figure A6 shows a microphotograph of two VCSELs from an array. The laser on the left is actively driven, while the one on the right is not driven. The lower photograph in the figure shows a flip chip mounted 20 element backside emitting VCSEL array in a sealed package.

Figure A7 shows the output data from an 8 x 8 element VCSEL array in which all optical output powers were between 7 and 9 mW. Figure A8 shows the circuit diagram for an 8 channel data link including transmitter and receiver. Figure A9 shows the planned design for a 16 channel 1550 nm WDM parallel data link in which all 16 channels spaced at 2 nm separation are combined on a single fiber for long distance transmission to a remote computer site. An Erbium Doped Fiber Amplifier is used to re-amplify all wavelengths for long distance transmission. Optical Concepts is presently developing this WDM system under a contract from the Ballistic Missile Defense Organization and the US Army Strategic Defense Command.

Optical Concepts, Inc.

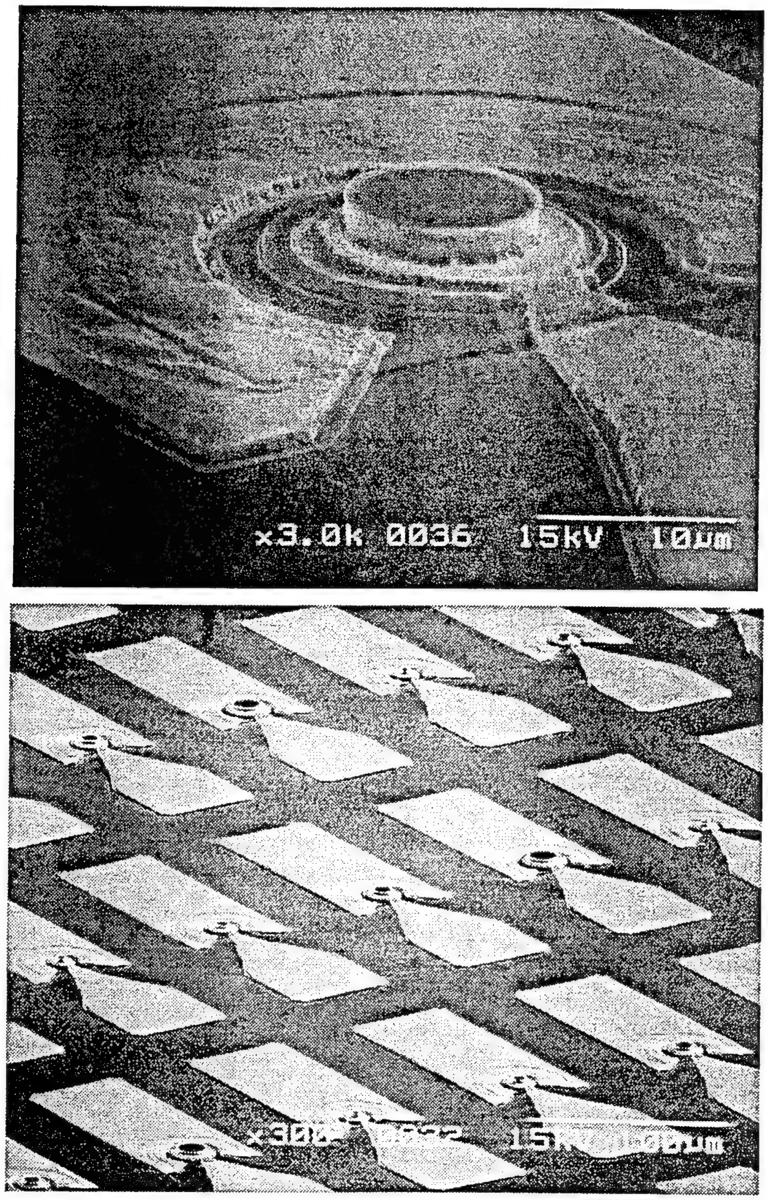
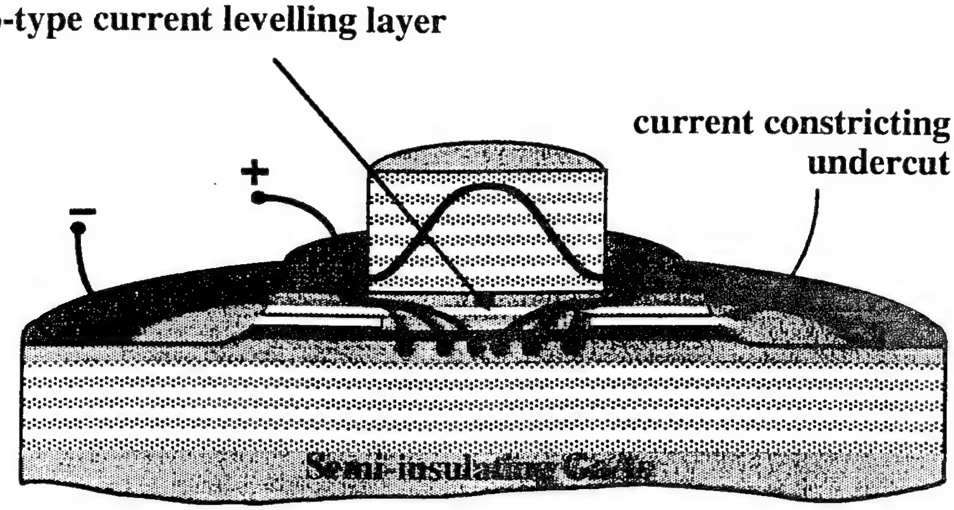


Figure A1

Top Surface Emitting Intra-Cavity Contacted Lasers



- Sub-milliamp thresholds
- High quantum efficiency
- Wire bond compatible

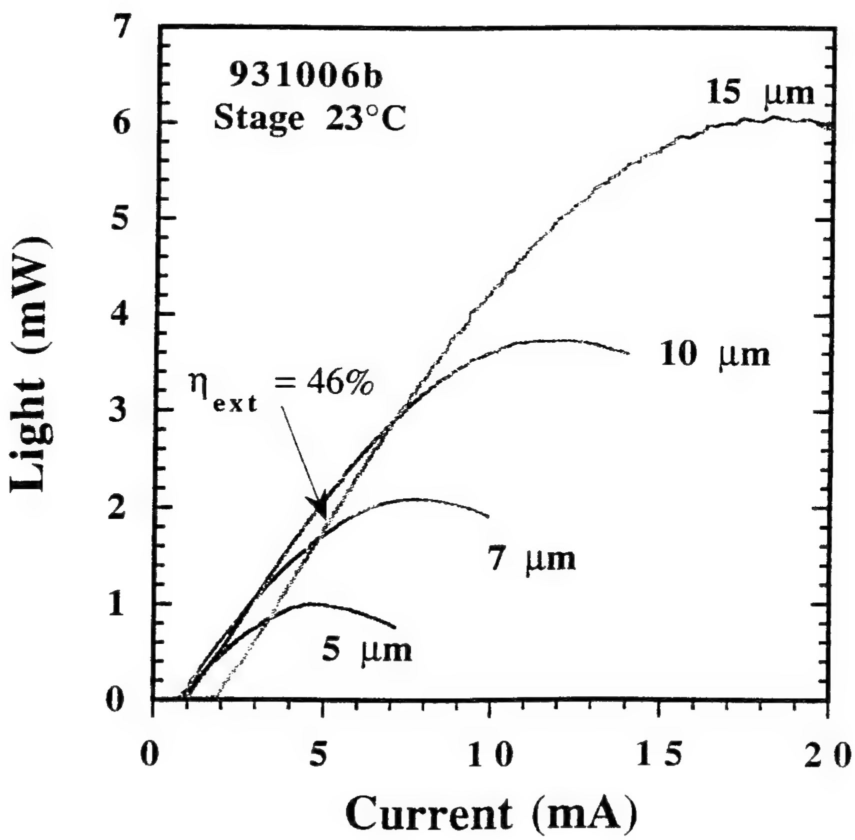
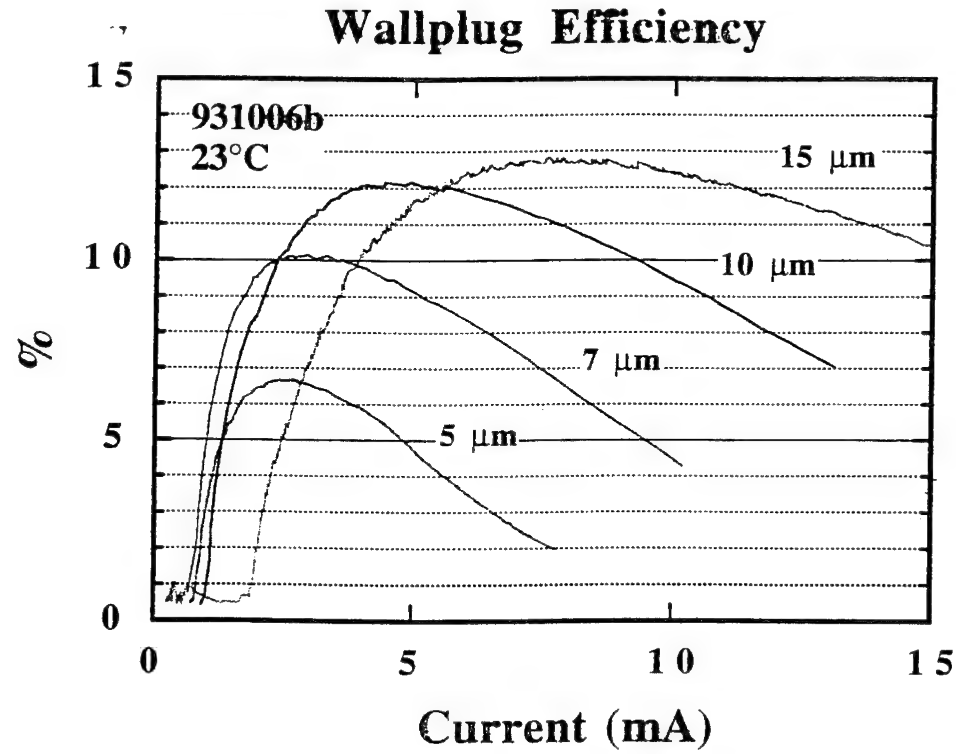
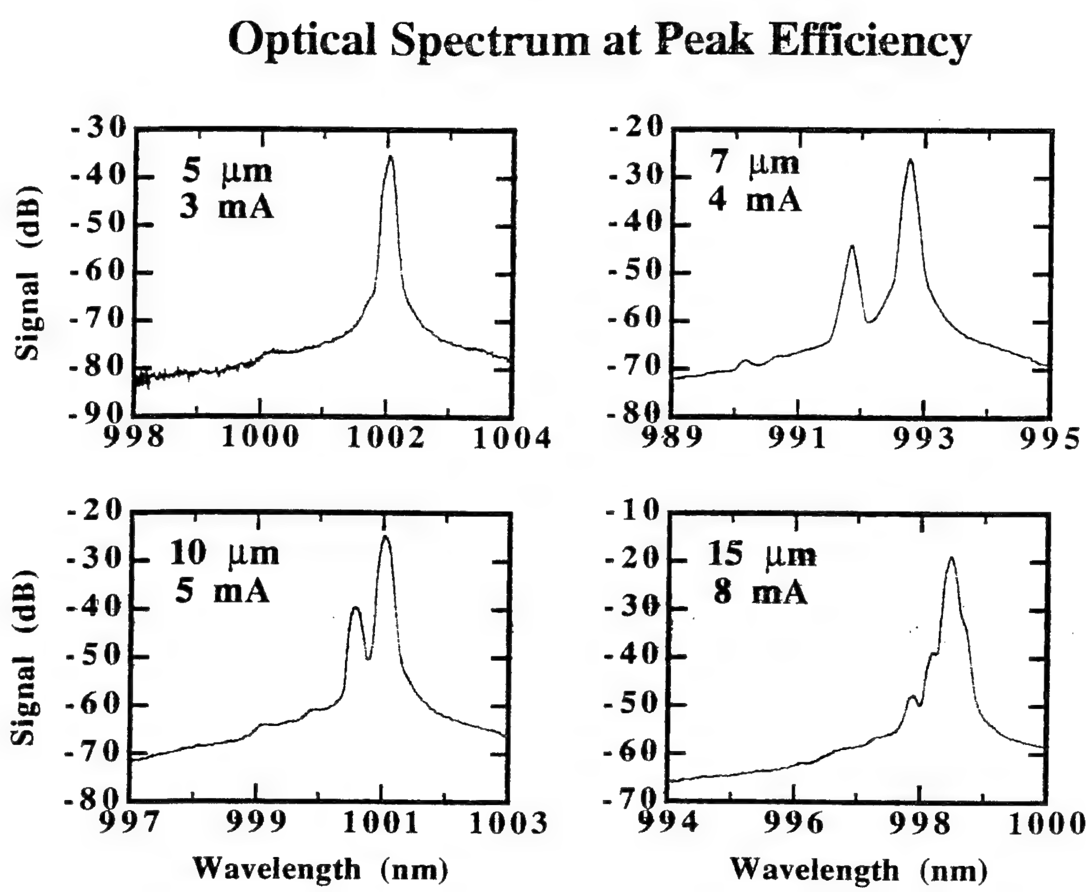


Figure A2

High Efficiency at Low Currents

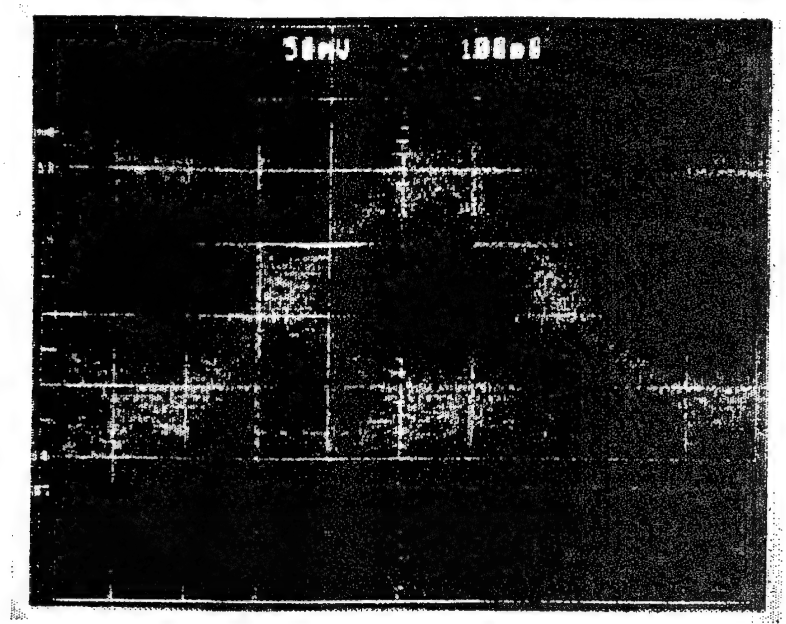




J. W. Scott, B. J. Thilbeaut, D. B. Young and L. A. Coldren "High Efficiency Sub-Milliamp Threshold Vertical Cavity Lasers with Intra-Cavity Contacts" *Submitted to Photonics Technology Lett. Feb 1994*

Figure A3

High Speed Digital Data Links



eye diagram for 5 μm device, received opt. power -14 dBm

- All four device sizes showed no error floor
- Measurements made with 30 meters of multimode fiber

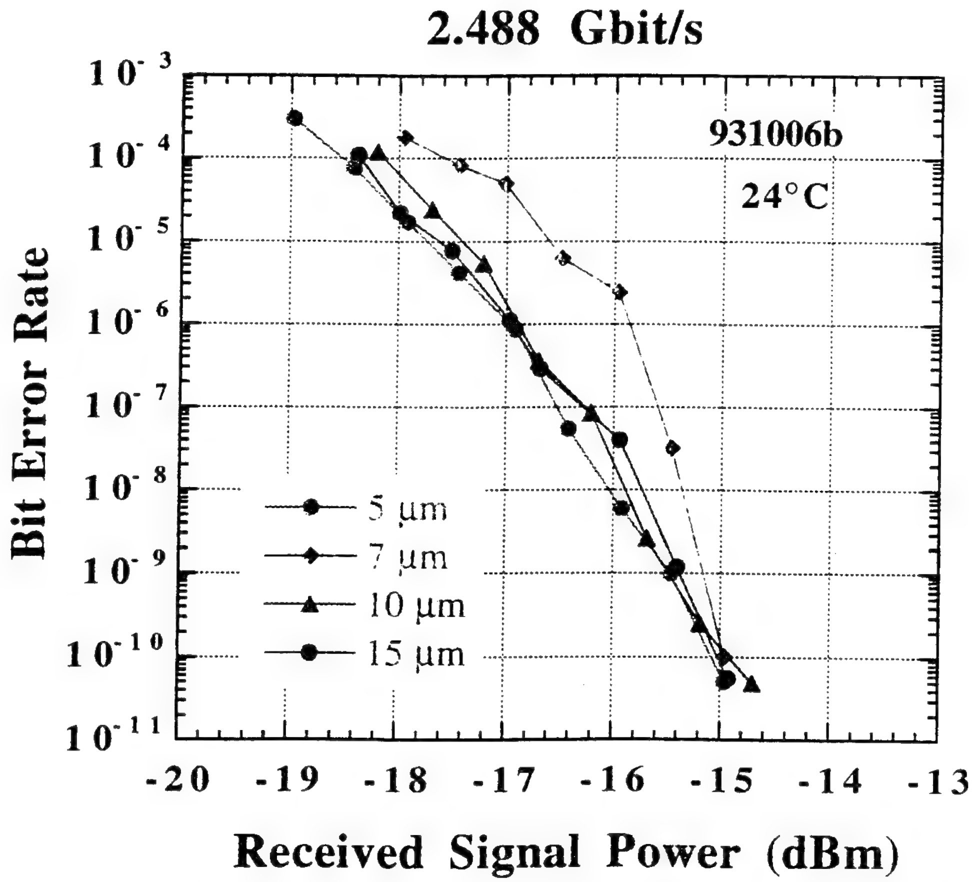
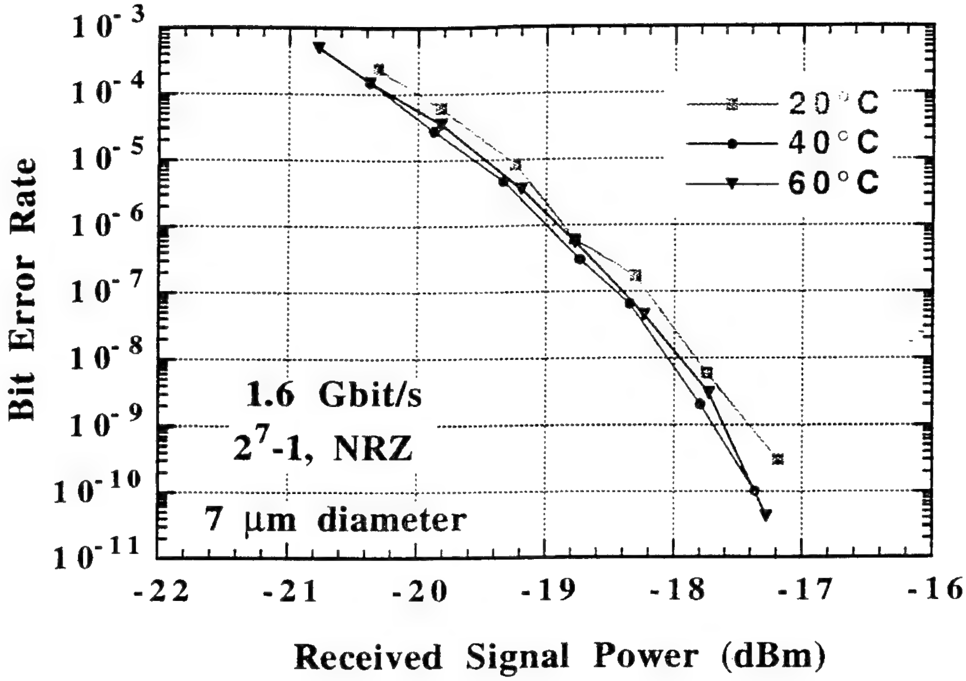


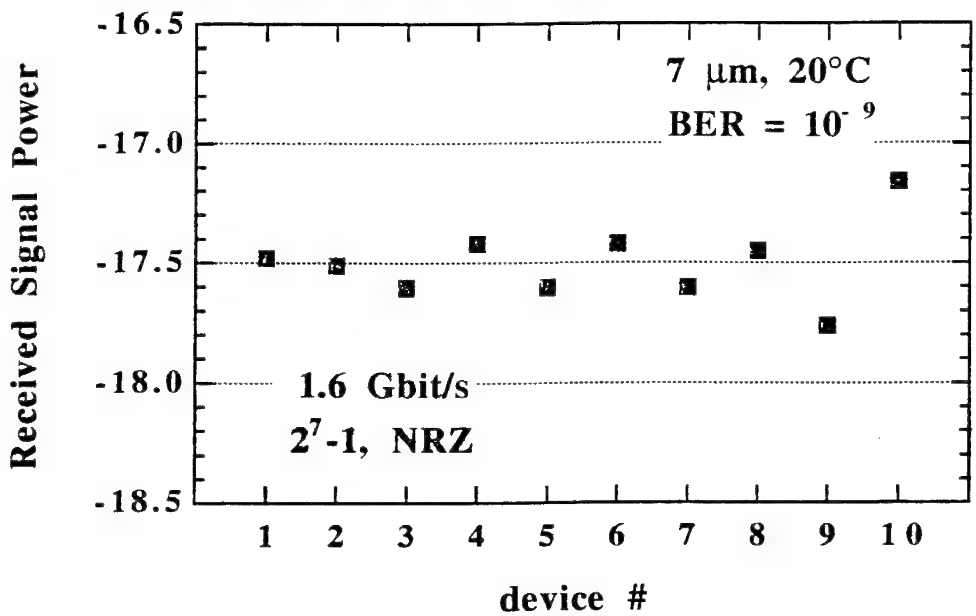
Figure A4

On / Off Modulation

- Insensitive to variation in temperature



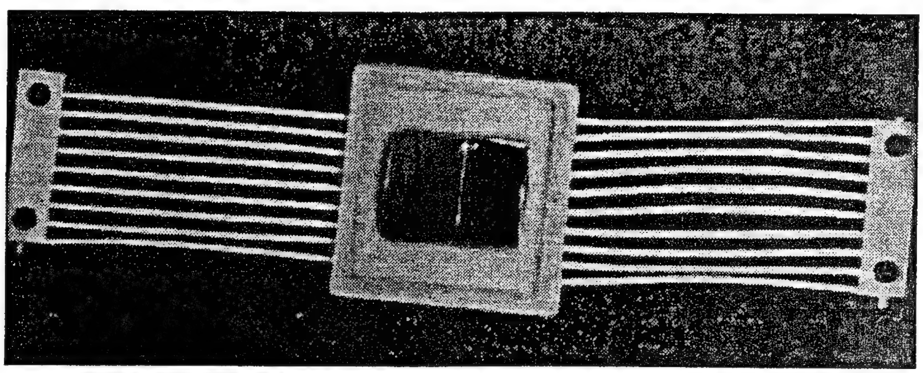
- Consistent results across the array



Drive conditions: 3 mA / 3 V bias, RF 1V peak to peak into 50Ω

Figure A5

PHOTOMICROGRAPH OF ACTIVATED AND UNACTIVATED VCSELs

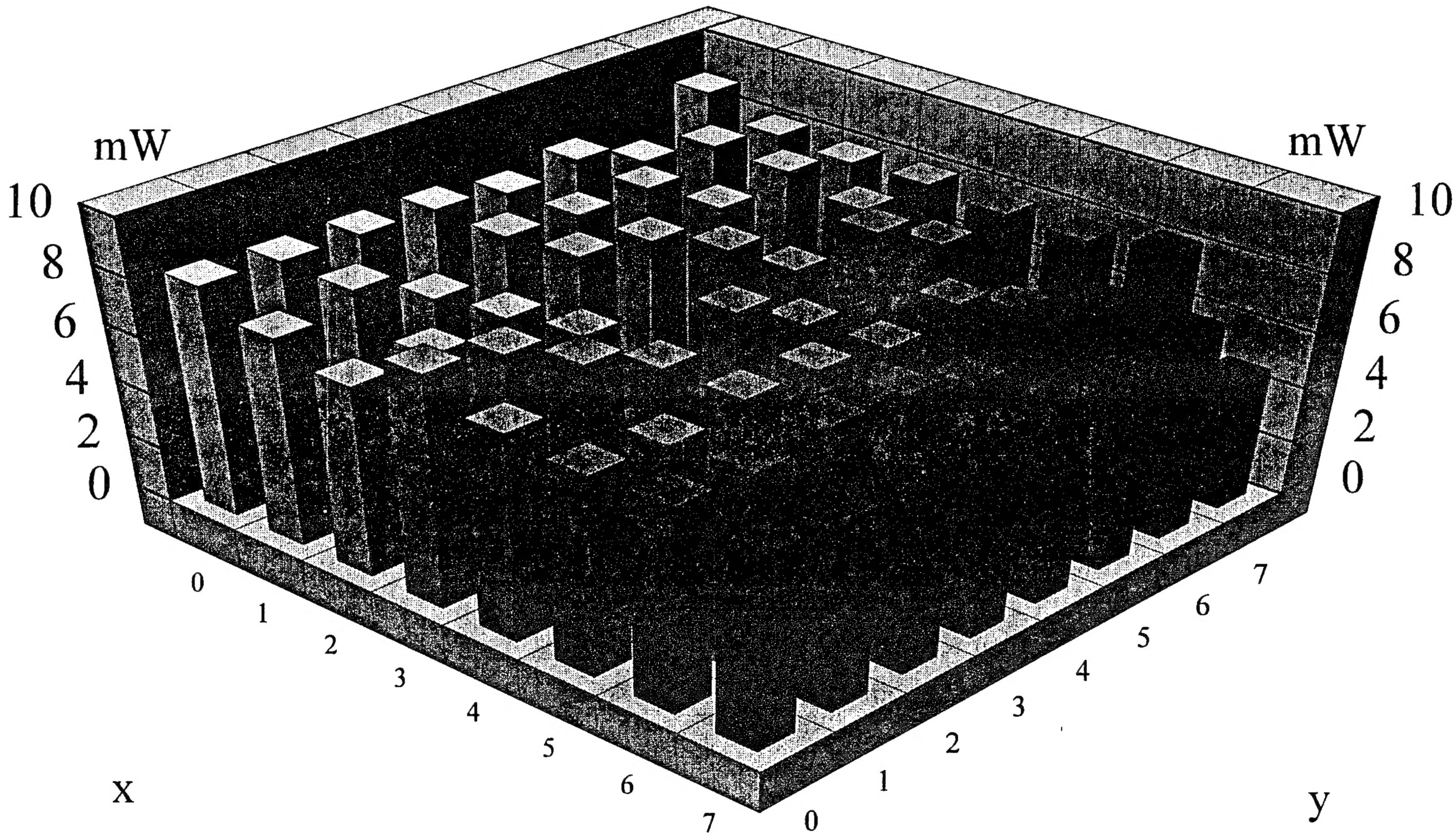


MOUNTED AND PACKAGED 20 ELEMENT VCSEL LINEAR ARRAY FOR PARALLEL COMMUNICATIONS APPLICATIONS

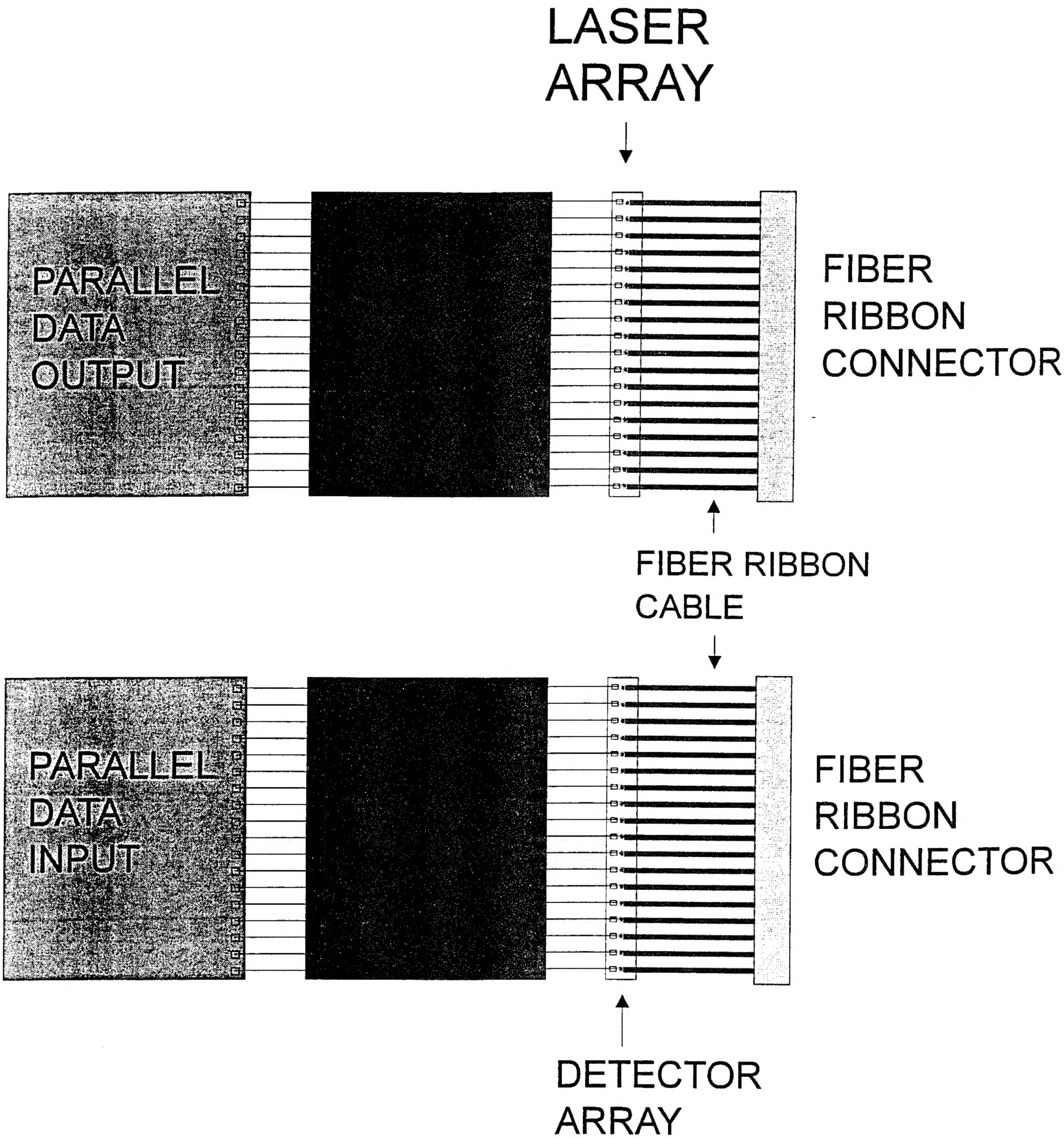
Figure A6

Maximum Power vs. Position

xd1116d - Array C5

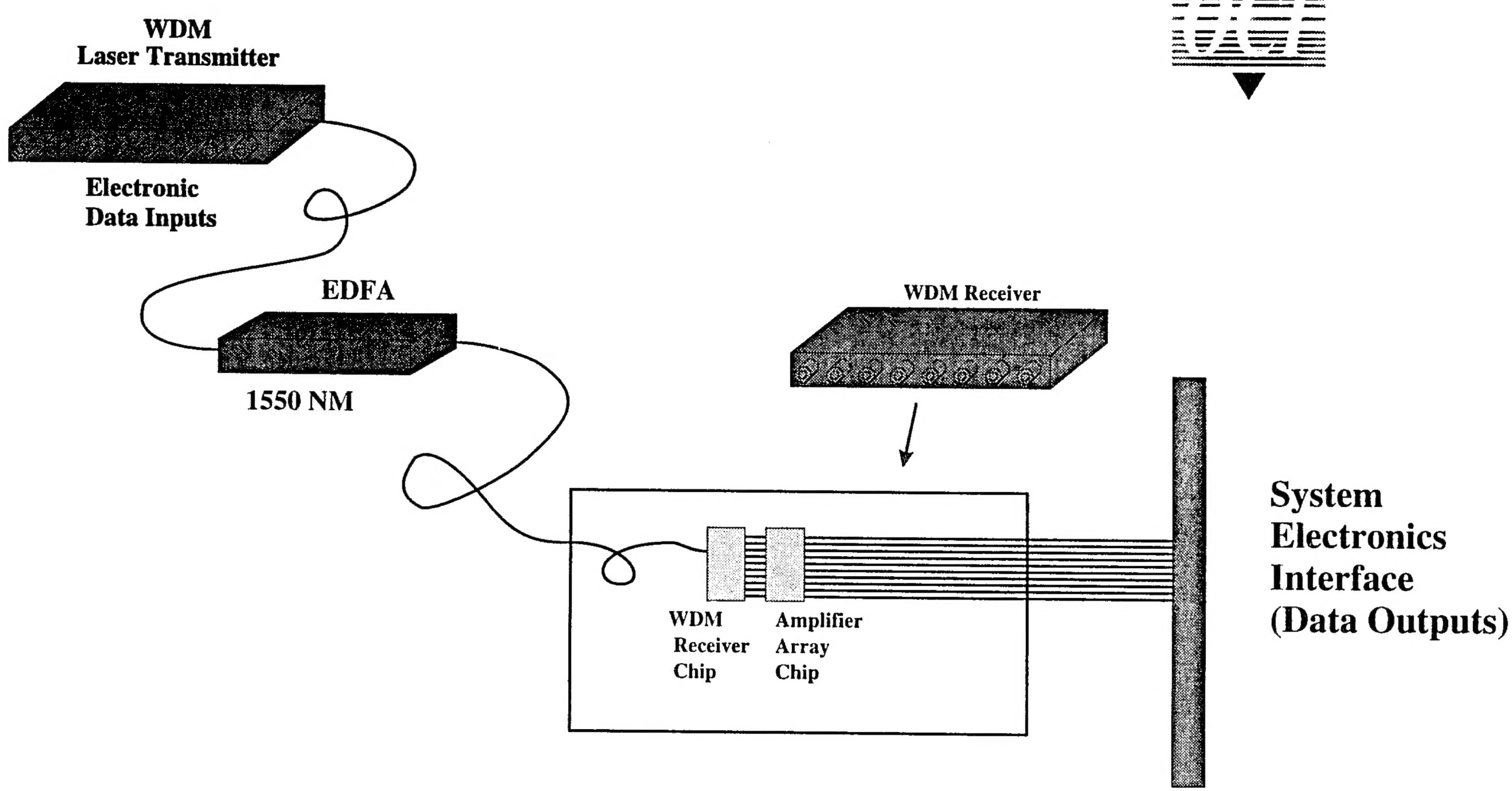


T=20 C - Figure A7



PARALLEL OPTICAL DATA LINK CARD

Figure A8



WDM SINGLE FIBER TRANSMISSION SYSTEM: COMPACT VERSION

Figure A9

Through contractual support, Optical Concepts is actively participating in research and development in several areas related to new product development. These include the extension of the vertical cavity laser technology into other wavelength regimes, the development of wavelength selective detector arrays and the incorporation of the lasers into data link modules. Our research and development activities already include government funded programs from the ARPA, Us Air Force, US Army Strategic Defense Command (SDC), Office of Naval Research, and the Strategic Defense Initiative Organization - Innovative Science and Technology office (BMDO-IST) and we have applied for several patents on vertical cavity lasers in the IR, visible and UV spectral regions. Several claims have been allowed by the US Patent Office, indicating that patents in these areas will be issued in favor of Optical Concepts, Inc.